LONG-TERM SIMULATIONS OF FOREST MANAGEMENT IMPACTS ON CARBON STORAGE FROM LOBLOLLY PINE PLANTATIONS IN THE SOUTHERN U.S.

Huei-Jin Wang, Philip J. Radtke, Stephen P. Prisley

ABSTRACT

Accounting for forest components in carbon accounting systems may be insufficient when substantial amounts of sequestered carbon are harvested and converted to wood products in use and in landfill. The potential of forest offset – in-woods aboveground carbon storage, carbon stored in harvested wood, and energy offset by burning harvested wood – from loblolly pine plantations was evaluated for greenhouse gas (GHG) mitigation over a half-century period. The in-woods carbon in well-managed loblolly pine plantations across the South totaled 341 million metric tons. This is equivalent to 20 percent of total energy-consumed GHG emission in the United States in 2006. Present-day carbon storage in southern pine plantations averaged 30.54 Mg•ha-1 (± 2.54 percent) for in-woods carbon. Annual wood production was 62.1 and 45.9 million green metric tons from pulpwood and sawtimber yield, respectively, with roughly one-fourth of the green weight being carbon. The carbon storage in wood products increased steadily over the half-century projection and showed no sign of leveling off, while the storage in plantations was found to remain constant or increase slightly over time. An additional 11 million metric tons of harvested carbon was used for energy per year on average, equivalent to 25 percent of annual forest-products-industry renewable energy use in U.S.A. Intensified application of fertilizers and herbicide and genetic improvement showed the potential to increase total storage in in-wood and harvested carbon pools as much as 30 percent, and energy offset up to 40 percent. Reducing management intensity greatly increased in-woods carbon storage potential, but eliminated the wood-products carbon sink.

INTRODUCTION

Forest ecosystems in the United States sequester 140-300 million metric tons (Mg) of carbon per year, or between 18 percent and 39 percent of the equivalent CO_2 emissions from the Nation's coal-fired power plants (Pacala and others, 2001; Heath and Smith, 2004; U.S. Environmental Protection Agency, 2007b). Despite scientists' knowledge that U.S. forests are an important terrestrial carbon sink, challenges remain in estimating the magnitudes of carbon storage attributed to forests in different geographic regions and in quantifying the magnitudes of fluxes for various forest carbon pools (Houghton and others, 1999; Schimel and others, 2000; Pacala and others, 2001; Janssens and others, 2003). One challenge involves incorporating uncertainty into estimates, so that decision-makers can plan in accordance with the quality of information in-hand (Gong, 1998; McKenney and others, 2004). Another challenge is to account for carbon sequestered in wood removed from forests as wood and paper products that may persist for long periods of time (Skog and Nicholson, 1998; Perez-Garcia and others, 2005). Such information is generally not a standard component in forest carbon estimates (Heath and others, 2003); however, both concerns are essential in making decision or plans for managed forest ecosystems, including the loblolly pine (*Pinus taeda* L.) plantations extensive throughout the southern United States.

Carbon stored above ground in loblolly pine plantations includes both merchantable and non-merchantable trees and vegetation, along with dead wood and plant detritus (Smith and others, 2004a). Regarding "long-lived" aboveground carbon pools, i.e. those in which carbon remains sequestered for decades or more, separate accounting is often made for live trees and coarse woody debris (CWD) based on the differing biological and ecological processes acting on each. Live trees sequester carbon on temporal scales of several decades, corresponding to rotation lengths. Carbon in CWD may persist in forests for years to decades depending on the relative rates of accumulation and decomposition (Duvall and Grigal, 1999; Vanderwel and others, 2008; Radtke and others, 2009). While aboveground carbon stored in live trees can be reliably assessed and projected over time and space, accumulations of CWD are considerably variable across landscapes and depend significantly on disturbance and management (Duvall and Grigal, 1999; Fridman and Walheim, 2000; Campbell and others, 2008).

In evaluating the potential of managed forest ecosystems such as loblolly pine plantations in mitigating atmospheric

Huei-Jin Wang, Graduate Research Assistant, Virginia Tech, Department of Forest Resources and Environmental Conservation, Blacksburg, VA 24061, U.S.A.
Philip J. Radtke, Associate Professor
Stephen P. Prisley, Associate Professor

GHG accumulations from the burning of fossil fuels, accounting for carbon stored in live trees and CWD is insufficient because substantial amounts of sequestered carbon are harvested and converted to end-use wood products, e.g. building materials, furniture, and paper products, or used as a fuel source to displace GHG emission from fossil fuels (Birdsey and Heath, 1995; Smith and others, 2006). Although harvested wood is not a part of in-woods carbon pools, the linkages between management activities, forest carbon sequestration, and the timing and amount of wood harvested are inextricable. Wood products may persist longer than plantation rotation lengths, and the amount of carbon remaining in wood products – products in use and landfills – contributes significantly to carbon sequestration over time (Skog and Nicholson, 1998). Moreover, the magnitudes and rates of carbon remaining in wood products depend on the timing, intensity, and extent of harvesting activities, which affects what products the harvested wood is allocated to and life spans of wood in these products. On the other hand, wood processing at mills, e.g. drying, peeling, slicing, and sawing, uses energy from burning wood residues and pulping liquors that reduces some need for using fossil fuels. Such energy sources currently supply 1.5 percent of the total energy consumption in the U.S.A. (Perlack and others, 2005). Compared to the combustion of fossil fuels, bioenergy from harvested wood is relatively carbon-neutral and can be renewable (Schiermeier and others, 2008). Reliable accounts of long-term carbon mitigation potential from these managed ecosystems should not fail to take harvested carbon into account (Smith and others, 2006). As demand for wood products grows, so too will plantation management intensity. Both factors will likely impact the amount of atmospheric carbon sequestered in southern U.S. forests and the wood products derived from them. Effective policy-making, planning, and management will require good information to ensure that these factors are accurately accounted for in optimizing carbon sequestration that can be supported by southern U.S. forests (Wear and Greis, 2002).

Plantation management in the U.S. South is expected to increase in intensity in order to provide more raw materials to meet rising societal demands for wood resources (Prestemon and Abt, 2002). Loblolly pine plantations comprise 9.7 million hectares of southern U.S. timberland, roughly 65 percent of the southern plantation area, and their area is projected to increase by 67 percent in the next thirty years (Prestemon and Abt, 2002; Wear and Greis, 2002; Smith and others, 2004c). Through woody and herbaceous vegetation control and fertilization, site characteristics are being actively managed to enhance productivity (Allen, 2001). Intensive site preparation, including bedding, disking, subsoiling, ripping, or combinations of these treatments, can efficiently reduce competition from non-commercial hardwood species (Morris and Lowery, 1988). In addition, herbicide application can improve seedling establishment and early growth (Nilsson and Allen, 2003). Fertilization has become an important silvicultural tool in treating nutrient-deficient midrotation stands for increasing volume growth (Fox and others, 2007). Planting genetically-improved growing stock has become a standard management tool to increase growth efficiency, with gains in volume growth averaging 10 to 30 percent over unimproved planting stock at harvest (Li and others, 1999; McKeand and others, 2003). Tree breeding and other efforts to improve genetic properties of plantation growing stock are increasingly producing commercially available families and genotypes for increased volume production in loblolly pine (McKeand and others, 2003; Allen and others, 2005; McKeand and others, 2006). Intensive management operations appear to have potential for sequestering greater carbon, and projections of management scenarios will provide an insight on dynamics of in-woods and products-based carbon pools.

Recently, national-scale inventory-based carbon assessments have been augmented to account for carbon stored in aboveground forest pools, as well as the carbon stored in wood products (Skog and Nicholson, 1998; Heath and others, 2003; Jenkins and others, 2003; Smith and others, 2003). To date, such assessments have not directly considered the resolution, intensity, nor timing of management activities prescribed at forest stand scales. Because management is typically carried out on the scale of forest stands, carbon accounting at the same scale will allow for tracking of the full range of management and harvesting activities (Harmon, 2001). In addition, stand-level accounting can be scaled up with increasing certainty, while downscaling of national-scale estimates generally leads to greater uncertainty (Freese, 1967; Smith and others, 2004a). Here, predictions will be made at the resolution of individual forest stands for greatest flexibility in prescribing management conditions. Results will be aggregated to state and regional scales to make broader geographic assessments, presumably with a relatively high degree of precision (Smith and others, 2004a). The resulting analyses should serve the information needs of individuals ranging from those who develop policies for climate change mitigation, to those who set long-term regional goals for carbon sequestration, to those who aim to increase the total carbon stored in the wood grown on and products harvested from their forest lands.

The goal of this research was to assess impacts of forest management on carbon storage in loblolly pine plantations across the southern United States over the next half-century. Of specific interest here are the in-wood carbon pools of aboveground live tree and CWD, and pools of carbon in wood products produced from southern forests. To preserve information related to stand-level management activities, extensive field-plot inventory data were coupled with stand-

level prediction models to reduce uncertainty in estimates and facilitate aggregation across different spatial and temporal scales. Four specific objectives were pursued as a part of the overall goal:

Objective 1—Estimate the amount of carbon stored aboveground in live trees and CWD at scales ranging from individual stands to the entire southern United States.

Objective 2—Predict the annual production of harvested wood under operational management over a 50-year span, distinguishing between wood harvested for use in solid wood and paper products, and accounting for trends related to management intensity;

Objective 3—Project in-woods carbon pools and carbon disposition in harvested wood over a 50-year time span, linking inventory-based data and management activities to existing models of growth and yield and accounting for the lifespan of wood products;

Objective 4—Evaluate long-term effects of intensive management of loblolly pine in the U.S. South, including competing vegetation control, fertilization, and planting of genetically improved growing stock, on carbon sequestration and storage.

MATERIALS AND METHODS

DATA

The primary data source used in addressing the study objectives is the database of forest inventory records available online from the USDA Forest Service Forest Inventory and Analysis (FIA) program (Forest Inventory and Analysis, 2009a). The FIA data used here are composed of two-phase sample data collected using double-sampling for stratification (Smith, 2002; Reams and others, 2005). Phase I data begin with the interpretation and classification of remote-sensing imagery. Strata weights are estimated for each remote-sensing class, and areas of interest, such as the areal extent of loblolly plantations, can be estimated by aggregation based on strata weights. Phase II field plots are established on subsets of Phase I strata to provide field observations of forest conditions and conventional timber-based measurements on trees larger than 2.54 cm diameter at breast height (DBH). The spatial sampling intensity of FIA field plots is one plot per 2,430 hectares, and each field plot comprises a cluster of four 7-m fixed-radius subplots, occupying a 0.067-ha area (Bechtold and Scott, 2005). Within each subplot is nested a 2-m radius microplot where detailed measurements of small trees (< 2.54 cm DBH) are made.

Phase II inventory data obtained, from 2005 – 2007 survey data for loblolly pine plantations of 11 southern states (Figure 1, Table 1), were used as the source of information for stand information, including plot datasets, plot-condition datasets, tree datasets, seedling datasets, and site-tree datasets (Forest Inventory and Analysis, 2009a). Plot datasets bridged Phase I data and plot-condition datasets to estimate forestland areas represented by each plot given its growing condition. Plot datasets provided plot geographic coordinates, remeasurement period (yr), a unique plot identification code and previous plot conditions if any remeaurement occurred. Field observations from plot condition datasets included plot conditional classes, condition status codes, condition proportions, subplot proportions, stand origin codes (natural stands or plantations), stand origin species, stand ages, treatment codes, year of treatment, and year of inventory. Conventional timber-based variables from tree datasets measured in subplots included tree status codes (live or removed), species, DBH, height, and live/removed cubic-foot volumes. Site-tree data included site index relevant measurements, i.e. height and age of dominant or codominant sample trees. Seedling data measured in microplots provided information on planting density.

The FIA data were screened to identify conditions consistent with "well-managed" loblolly pine plantations such as those used in the development of the FASTLOB growth-and-yield model developed by the Forest Modeling Research Cooperative at Virginia Tech (Amateis and Burkhart, 2009). Only those plantations having ≤ 20 percent of the stand basal area comprised of hardwood species and those having ages between 0 and 50 years were defined as "well-managed" and subsequently included in the analyses. These conditions were consistent with the data used to develop FASTLOB and its computer implementation (Ralph Amateis, personal communication, March 1, 2010). Among 12.4 million hectares of planted loblolly pine forest, a set of 5,480 FIA inventory plots matched the screening conditions and the total area was 11.2 million hectares, including 3,139 plots on which the screened condition was observed on the entire plot, and 2,341 on which the screened condition was observed on a portion of the plot.

STAND-LEVEL GROWTH-AND-YIELD MODEL

The FASTLOB model was developed to reflect management activities common to loblolly pine plantations established from the late 1950s to early 1990s (Amateis and Burkhart, 2009). FASTLOB uses site index (base age 25 years), age, stem density, amount of competing vegetation, thinning operations, fertilization, and other stand characteristics to project merchantable yields (pulpwood and sawtimber) and in-woods biomass by component, including stem and bark,

branches and bark, foliage, and CWD, at different ages. Not only projections but also predictive values for initial growing stock can be obtained while inputs are established. Stand-level equations that comprise the nucleus of FASTLOB project dominant height, survival and basal area, and serve as a baseline thinned and unthinned model for stands. In addition, model inputs including information of latitude and longitude provide more precise locale-specific predictions if data are available. FASTLOB is presently used in ongoing forest management across the private sector of the South.

QUANTIFY CURRENT FOREST CARBON POOLS

Coupled with FIA stand attributes, FASTLOB was used to initialize current stand-level forest carbon pools, but an indication of how close the estimate from FIA is to the population parameter was not readily available through applying FIA area expansion factors to scaling up stand-level estimates to state and southwide levels (Scott and others, 2005). "Forest carbon pools" in this study refer to the carbon content (one-half the mass of oven-dry biomass) in aboveground live trees and CWD, including standing snages and downed-woody material. Variances of in-woods carbon estimates were used to characterize the uncertainty of current forest carbon pools.

Bootstrap variance estimation and its corresponding Monte Carlo approximation were used to compute the estimate of in-woods carbon mass (live trees and CWD) at various regional scales (Booth and Sarkar, 1998). Because the probability density function of the population distribution was unknown, a nonparametric approach was applied to assess various regional-level carbon quantities. In the application of bootstrap sampling, predictive values of current in-woods carbon mass from FASTLOB initialization, weighted with representative areas for each FIA plot, were treated as a substitute for the population of in-woods carbon. Then, from these 5,480 observations (the number of FIA plots in the dataset), bootstrap samples of size 5,480 were selected with replacement from the FIA dataset. An estimate of in-woods carbon was obtained from each bootstrap sample at state and southwide levels. Two thousand bootstrap samples from the data were generated in total (Booth and Sarkar, 1998). Standard errors and the 2.5^{th} and 97.5^{th} percentiles of the confidence interval for the in-woods carbon were then approximated from the bootstrap sample distributions.

ASSUMPTIONS OF BASELINE MANAGEMENT

Management conditions considered here included the area and density of planting, timing and intensity of thinnings, ages to harvest (rotation ages), and silvicultural activities associated with high-intensity management. Final (clearcut) harvests are simply referred to as "harvest" in this study, in contrast to wood harvested by thinning, which is referred to simply as "thinning." Maximum-likelihood was used in analyzing FIA data to estimate parameters for management-related inputs including planting densities, levels of residual stems per unit area, and ages for thinning. Log-normal distributions were fitted to planting density and residual stem density. A gamma distribution was fitted to approximate the distribution of thinning ages for subsequent simulations. Empirical cumulative distribution functions (ECDFs) and Quantile-Quantile (Q-Q) plots were used to evaluate quality of fit for empirical frequencies with those fitted to density functions.

Distribution functions were fitted to 2005 – 2007 measured plot attributes from FIA to simulate inputs for simulations to be consistent with real-world conditions of planting density, timing, and intensity of thinning (Figure 2, Figure 3, Figure 4). Mean and median planting densities of 1,473 and 1,349 trees•ha^{-1}, respectively, coincided with planting spacings typical of southern U.S. pine plantations and a lognormal distribution function fitted to FIA data (Figure 2). No relationship existed between age of thinning and site index. Therefore, age of thinning from FIA records was fitted to a gamma distribution function (Figure 3). Post-thinning residual densities were simulated by a lognormal distribution (Figure 4). All three of these distribution functions represented the general shape and scale of the FIA data for planting density, thinning age and residual density, although some lack-of-fit was noted, especially in the upper tails of these right-skewed distributions.

Rotation length, the plantation age at final harvest, was needed to schedule operations on individual stands; however, rotation length was only directly observed on a small number (n = 22) of the FIA phase II field plots – namely those that had been visited at two different times and were harvested between visits. In these data an inverse relationship between site index and rotation length was noted (Figure 5A). Their mean rotation length was 27.5 years (s = 6.1), over plantations that averaged 18.50 m in site index (s = 2.18). Although the relationship between rotation length and site index was relatively weak, a trend describing it (Figure 5A) was used to predict rotation length for the full set of FIA phase II plots where rotation lengths had not been observed. Predicted rotation lengths by plantation area averaged 27.5 years using this approach, with 80 percent of plantation area having rotation lengths between 23 and 32 years (Figure 5B). Dividing the total area of plantations by the mean predicted rotation length indicated an annual harvest area over time of 406,000 ha, which was roughly consistent with published report of 524,000 ha planted in loblolly and shortleaf pines in the southern U.S. in 1998 – including those subjected to all levels of management intensity (Moulton and Hernandez, 2000; Smith and others, 2004c).

SIMULATION OF SILVICULTURAL OPERATIONS

Loblolly pine plantations were assumed to be managed primarily for timber benefits over the 50-year simulation. With regard to management objectives, plantations were categorized into two populations throughout the commercial range of species, those that would be thinned at some point during a rotation, and those that would remain unthinned up to the point of their final harvest. An area of 288,623 ha was set as the target for the area of thinnings to be simulated each year, based on the estimated annual area of thinning in FIA plantation area. The same area was targeted for final-harvest operations in previously-thinned stands each year so that the area of thinned plantations would remain constant over time. The area to be harvested annually from never-thinned stands was set at 117,377 ha as an initial target value, so that the area harvested from thinned and never-thinned plantations would target a total of 406,000 ha per year, as was determined in the previous section.

In simulation of area harvested annually from either thinned or unthinned stands, it was necessary to assign the annual area harvested to various plantation ages. Much as growth and yield share an inherent relationship the plantation area harvested in various age classes over time has an cumulative effect on the age distribution of plantation growing stock (Clutter and others, 1983). To reflect this relationship, the mathematical derivative of plantation area with respect to age across the South was used in assigning an age distribution to the area annually harvested. To implement this method, plantation area was first expressed as a function of stand age to match the empirical conditions characterized from the FIA database.

Graphs of plantation area by age for thinned and unthinned stands showed distinct trends of declining area beginning around age 22 for thinned stands, and age 16 for those that were never thinned (Figure 6). These values were used to establish the minimum ages for final harvesting, i.e. the minimum rotation lengths, in thinned and unthinned plantations, respectively Then the first derivatives of area with respect to age were calculated to represent suitable functions of harvest area (i.e. change in plantation area) by plantation ages. These first derivatives of area harvested from thinned and unthinned stands were defined by functions, Eq. [1] and Eq. [2], respectively:

$$y = c_1 \text{ x } (1307x^{-2} - 133100x^{-3} + 3606000x^{-4} - 28876000x^{-5}) \text{x } exp(15.83-1307x^{-1}+66550x^{-2}-1202000x^{-3}+7219000x^{-4}) \quad [1]$$

$$y=c_2 \text{ x } 0.13 \text{ x } exp(15.16-0.13x) \quad [2]$$

where
x = stand age (yrs)
y_x = total area harvested at age x
c_1 and c_2 are refined factors through simulations

To focus on changes in plantation area that were due to removals by harvesting, only the declining portions of the age class by area distributions were considered (Figure 6). Thus, in accord with the FIA data it was assumed that final harvesting for thinned stands took place no sooner than 22 years after planting in loblolly pine plantations, and no sooner than 16 years for unthinned stands.

All thinnings were simulated based on a thinning intensity of 20 percent removals by row thinning and an additional ≥5 percent reduction in stem density removed by thinning from below. Following thinning, a minimum of 6 years was required in any particular stand before final harvest was allowed in order to capture the volume growth response to the thinning treatment. Timings and total area of plantation thinnings were specified by the gamma-model-specified distribution of stand ages at thinning, along with the target for total area to be thinned each year across the South. End-of-rotation harvest timing and area also targeted an age-distribution and total area. A time period for harvesting, site preparation and subsequent planting was assumed to be one year; therefore, artificial regeneration was simulated to follow an end-of-rotation harvest with a one-year fallow period.

SIMULATION ANNUAL OPERATIONS

Forest management regimes span decades for a rotation, and individual stands experience all stages of the forest management cycle including final harvest, site preparation, regeneration, and thinning. Concerning stable production of timber harvests from year to year, total southern loblolly pine plantations were treated as a single entity and management activities were manipulated through coordinating all stands. Final harvests were assumed to be operated on 406,000 ha annually, i.e. 288,623 ha from previously-thinned stands and 117,377 ha from never-thinned stands. Regarding changes in plantation area on rotation ages, Eq. [1], Eq. [2], and rotation ages modified from FIA data (input rotation ages) were programmed into simulations of area harvested annually. Intermediate simulation results were used to refine the two constants c1 and c2 in Eqs. [1] and [2], respectively, along with the specified target area for annual harvesting in unthinned plantations. The sequence of steps performed in the simulation algorithm follows (Figure 7): (1) if stand age is equal to its predicted rotation age or greater, then this stand becomes one candidate to be harvested; (2) with regard to the size of candidates' representative area, candidates with large areas have top priority to be harvested; (3) select candidates from the pool of candidate stands to meet requests from each age-class area of Eq. [1] or Eq. [2]; (4) if total area from Step 3 meets the target harvest area, then stop; (5) otherwise, more candidate stands harvested are needed. In this step, number of overdue years of predicted rotation age is used instead as the criterion for choice of

candidate stands to be harvested. Select candidates from more overdue years to meet target harvest area; (6) means of simulated rotation ages and areas harvested by year are evaluated whether simulation underperforms or not; (7) if underperformance occurs, refine c1 in Eq. [1] or c2 in Eq. [2]; (8) re-run steps 1-7 for the next 50-year-simulation iteration until simulation output is in good shape. After final harvest and a one-year fallow period for site preparation, all stands were established and their planting densities followed the lognormal-model-specified distribution.

Assignment of stands to be treated by thinning, or remain unthinned during the lengths of their rotations was made using a Bernoulli distribution with values 1 for thinning, and 0 for no thinning. The probability that a stand would be thinned (p) was defined by the total area harvested from thinned stands divided by total harvest area across the South from the previous year in the simulation. As previously noted, the area to be treated by thinnings annually was set at 288,623 ha and its age structure was defined by Eq.[1]. This simulation required four component inputs including target area, Eq. [1], input rotation ages, and the gamma-model-specified distribution of stand ages at thinning. The steps of the algorithm procedure follow (Figure 8): (1) if stand age is equal to its gamma-specified age or greater, then this stand becomes one candidate to be thinned; (2) candidates have top priority to be thinned if their representative area are large; (3) select candidate stands to meet demands of future harvest areas from Eq. [1] coupled with predicted rotation ages; (4) if total area from Step 3 meets target thinned area, then stop; (5) otherwise, select more candidate stands to meet the target area. Number of overdue years of thinned age serves as the criterion for choice of candidate stands to be thinned. From large overdue years, select candidate stands to meet target thinned area.

HARVESTED WOOD PRODUCTION OVER TIME

Projections of future production of timber products (i.e. pulpwood and sawtimber) were made under the baseline management scenario described above, which was determined from FIA data. Simulated variables including areas harvested either from thinned or unthinned stands, thinned areas, rotation ages, and ages for thinning were linked to FASTLOB to generate timber products estimates. Pulpwood was defined as 15.24 cm (6 in) DBH and larger and minimum diameter top was 10.16 cm (4 in) outside bark; and sawtimber was defined as 22.86 cm (9 in) DBH and larger to a minimum 17.78 cm (7 in) top diameter outside bark using the International 1/4-inch log rule. Green weights outside bark for both types of timber products were predicted for comparison to regional analyses that express production on the basis of weight (Bullock and Burkhart, 2003). For validation purposes, primary-mill survey results from 2006-2008 were obtained from FIA timber product output (TPO) reports of pulpwood and sawtimber production from roundwood (e.g. Cooper and Becker, 2009; Johnson and others, 2010).

To assess the potential role of wood products in mitigating GHG emission from fossil fuel, i.e. carbon pools and energy offset, the method for calculating harvested carbon by Smith and others, (2006) was used. The amount of carbon in wood products each year was estimated, including products in use and products in landfill, through 2056, beginning with wood harvested in 2006. Carbon remained in harvested wood products was expressed as metric tons per hectare ($Mg \bullet ha^{-1}$) even though the disposition of carbon over time for such wood products are not directly linked to forest area. With regard to renewable energy consumption from wood residues and pulping liquors generated by the forest products industry, the amount of emitted carbon by year was estimated. Year-to-year changes in stocks of carbon sequestered in the wood-products pool was estimated to evaluate whether this pool is a carbon sink, balance, or source.

The carbon content in harvested wood was estimated using green weight of pulpwood and sawtimber production from FASTLOB output and moisture content (MC) of sapwood 110 percent (Glass and Zelinka, 2010). Disposition of carbon in harvested wood products for products in use, products in landfill, and energy offset was estimated as follows: (1) ***Ovendry weight = Green weight/(MC+1)***; 50 percent of this is carbon mass; (2) allocate sawtimber and pulpwood to primary wood products (e.g. lumber, plywood, panels, and paper) according to region and category in Table D6 of Smith and others, (2006); (3) compute carbon amount of primary products remaining in use or in landfill each year based on Tables 8 and 9 of Smith and others, (2006), respectively; (4) estimate amount of carbon associated with energy recapture using Table D7 of Smith and others, (2006) (See Smith and others, (2006) for details).

IN-WOODS CARBON OVER TIME

To evaluate long-term effects of baseline management on sequestering carbon and maintaining in-woods carbon, FASTLOB was used to project biomass of aboveground live trees and mass of CWD in a 50-year timeframe since 2006. Rate of change of sequestering carbon was computed to assess whether the managed forest was a carbon-balanced system or not. FASTLOB has embedded prediction equations that estimate biomass for various components (Baldwin and others, 1997; Landsberg and Waring, 1997; Radtke and others, 2009). Carbon mass was assumed to be 50 percent of biomass (Smith and others, 2003).

INTENSIVE MANAGEMENT SCENARIOS

With regard to an increase in management intensity in the southern plantations, two management intensity scenarios were developed to estimate potential loblolly pine growth

and yield and the corresponding effects of management on carbon storage. The two management scenarios included (1) scenario 1: intensive site preparation, herbicide application, and mid-rotation fertilization; and (2) scenario 2: the management regime from scenario 1 plus planting of genetically improved growing stock. The term "genetically improved" here assumes that growing stock came from third- or fourth-generation seed orchards which have not previously been deployed in the South (McKeand and others, 2003).

The intensive management regimes 1 and 2 were used according to the embedded functionality of the FASTLOB modeling system. For completeness, an overview of the FASTLOB implementation for intensive management is given here. Growth responses to intensive silviculture in FASTLOB are added to baseline-management predictions. According to research that showed growth responses to intensive site preparation and herbicide application varying from site to site, the effect of competing vegetation control on growth and yield was modeled in FASTLOB by increasing site index by 0 to 1.5 m (Siry and others, 2001; Nilsson and Allen, 2003). A uniform distribution was used to simulate random site index increases within this range for each stand. In accord with common mid-rotation fertilizer applications of 28 P kg•ha^{-1} and either 224 or 196 N kg•ha^{-1}, the amount of N fertilizer applied in a given stand was set to follow a Bernoulli distribution with p (224 N kg•ha^{-1}) = 0.58, and $1 - p$ (196 N kg•ha^{-1}) = 0.42 (Albaugh and others, 2007). For unthinned stands, the timing of fertilization was assumed to take place between ages 13 to 20 and no harvesting within six years of fertilizing; for thinned stands fertilization was performed after thinning. Timing assumptions for fertilization were primarily based on published studies varying management intensities that Siry and others, (2001) assumed fertilization at age 15 years for medium intensity and 5-to-10 years for high intensity; Allen and others, (2005) assumed age 17 years for medium intensity and 5-to-21 years for high intensity; Liechty and Fristoe (2010) used ages 17-to-22 years for timing of mid-rotation fertilization. Genetically improved stock was assumed to increase volume by 10 to 20 percent at harvest ages and this increase corresponded to a 1.5- to 3-m site index gain (McKeand and others, 2006). Site index gains due to planting of genetically improved seedlings were simulated by generating a uniform random variate on the interval [1.5, 3.0] for each stand.

RESULTS

ESTIMATES FOR CURRENT CARBON POOLS

In well-managed loblolly pine forestland across the South, the estimate of in-woods carbon mass total exceeded 340 million Mg (1 Mg = 1 metric ton or approximately 1.1 U.S. tons) (Table 2). The mean of area-weighted averaged carbon was 30.54 Mg•ha^{-1}. State-by-State in-woods carbon totals varied from 3.3 to 53.7 million Mg, and 21.30 to 35.51 Mg•ha^{-1} for carbon means per hectare by accounting for forestland area (Table 2). Carbon total stocks in Tennessee and Florida were significantly less than those in the other nine States, largely due to their comparatively small plantation areas. Aside from the effects due to its small plantation areas, Tennessee had relatively low carbon stocks of 21.30 Mg•ha^{-1}, in part because of its comparatively low average basal area (Table 1). In general, States with the lowest average plantation ages had the lowest yields per hectare, while those with the highest plantation ages had higher yields (Table 1, Table 2). The percentages of aboveground live trees and CWD, contributing to the in-woods aboveground carbon pool, were about 93 percent and 7 percent, respectively (Table 3, Table 4).

BOOTSTRAP RESULTS

Sampling distributions for in-wood carbon quantities (i.e. carbon total and carbon per hectare) in loblolly pine plantations across the South appeared to be consistent with a normal distribution, with the bootstrap-simulated means being approximately equal to estimates from FASTLOB (Figure 9, Figure 10). The simulated results for standard errors and the 2.5th and 97.5th percentiles of distributions were given in Table 2 , Table 3 , and Table 4. Bootstrap confidence intervals for southwide carbon spanned ±2.80 percent for total carbon mass and ±2.54 percent for carbon per hectare (Mg•ha^{-1}) in the in-woods pool, respectively. Variances in live-tree carbon were ±2.77 percent and ±2.44 percent for carbon total and per hectare, respectively, and those of CWD carbon quantities were ±7.38 percent and ±7.30 percent.

State-level uncertainties for estimates of carbon quantities were assessed using the same set of bootstrap samples (Table 2, Table 3, Table 4). Compared to southwide estimates, State-by-State estimates were relatively imprecise. Uncertainty in the in-woods estimates was primarily contributed by variability from live-tree pools. Despite the larger dispersion of CWD pools across States, because of their smaller size, CWD pools contributed less to overall in-woods variablity. Tennessee and Florida had greater variance of carbon estimates, mainly because of the relatively small numbers of FIA field plots in loblolly pine plantations in those States. Therefore, their standard errors of estimated totals and means for in-woods carbon were relatively large compared to other States' estimates. Excepting Tennessee and Florida, 95 percent bootstrap confidence intervals for States' carbon means in well-managed plantation forestland did not exceed ±15 percent of the estimated values.

AGE-CLASS SIMULATIONS OF AREA

The target area for annual harvesting from unthinned stands was set to 112,583 ha following test simulations used to determine whether this value was consistent with the constant c_2 in Eq. [2]. Hypothetical distributions of harvest area by age classes (Figure 11), were multiplied by constants c_1 = -2.48 in Eq. [1] and c_2 = -0.65 in Eq. [2], which ensured consistency between target harvest areas, Eqs. [1] and [2], and the predicted distribution of rotation ages. The derivative functions or harvest area by age classes reflect the assumed restriction of final harvesting in thinned plantations to those ≥22 years of age and unthinned plantations ≥16 years. In addition, these hypothetical distributions, especially the harvest curve for thinned stands [1], agreed with the predicted distribution of rotation ages (Figure 5B, Figure 11).

In plotting the area of simulated thinning and final harvest operations in each year of the simulation (Figure 12A), two periods, each spanning about 10-years, reflected relatively low projected areas of thinning (2015 – 2025) and final harvest (2025 – 2035) activity. These periods corresponded to a decade of relatively low establishment of loblolly pine plantations across the South in the 1990s, which is reflected in the relatively low area of 5 to 15 year old plantations in the initial age-class distribution (Figure 13A). At the end of the 50-year simulation, the same pattern was not evident in the age-class structure of loblolly pine plantation area across the South (Figure 13B).

Simulated results of year-by-year areas operated by thinning and harvesting, and their corresponding mean ages for operations were plotted in Figure 12. The annual area of final harvest averaged 400,000 ha over the 50-year simulation, including 290,000 ha (± 9,600) harvested from thinned stands and 110,000 ha (± 3,300) from unthinned stands. Rotation lengths in the simulations ranged between 26 and 33 years. Accounting for the occurrence of projected thinnings, simulated rotation ages of thinned stands averaged about one year more than those of unthinned stands, at 28.2 and 27.4 years, respectively. The annual area of thinning operations averaged 280,147 ha with a standard deviation of 27,000 ha over 50 years, with an average age of thinning = 18.0 years (s = 0.7 yrs).

PROJECTED TIMBER PRODUCTION

An example of the effect the simulated thinning regime had on stand-level volume and biomass accretion over the 50-year projection period can be compared with that of a stand not subjected to thinning (Figure 14). In both thinned and unthinned simulated stands, all aboveground volume and CWD was set to zero prior to the artificial regeneration of the stands. As is typical of most models that project growth and yield after thinning in plantations, volume was immediately reduced at the time of thinning, and then allowed to re-accumulate over time until final harvest. In the years immediately following thinning, standing volume growth rates exceeded the rates realized before thinning for a time; however, volume production at final harvest was lower in thinned stands than their unthinned counterparts. The period of no apparent volume or biomass that occurs between rotations is a minor artifact of the way volume accretion is estimated in FASTLOB. In particular, the youngest age at which any volume outputs are generated is five years after planting.

Timber production southwide for each year was computed as an aggregate of all stand-level projections. Results showed that through carrying out thinning operations, stands supplied one-fourth timber production annually including pulpwood and sawtimber, and final harvest three fourths, drawn from Figure 15. Further, thinnings primarily produced pulpwood; and final harvests produced pulpwood and sawtimber. Annual total pulpwood yield was 62.1 million green metric tons, ranging from about 49 to 76 million green metric tons, 38 percent from thinning and 62 percent from final harvest. However, total sawtimber production of 36 – 60 million green metric tons was almost 100 percent made up by final harvests. Mean projected annual pulpwood production was nearly equivalent to 2006 – 2008 TPO reported pulpwood production. For sawtimber the projected mean was about 35 percent lower than the TPO value (Figure 15).

CARBON POOLS AND FLUXES

Figure 16. showed the effects of annual thinning and final harvesting activities on reductions of carbon from the in-woods pool. Intra-annual increases in the trend represented net growth through the growing season, while intra-annual decreases represented removals. Timing of removals was arbitrarily set to follow the annual growth each year, without detailed consideration of the timing of growth and removals within any given year. Considering both additions and losses of carbon in the wood-products pool, which includes products in use and in landfills, harvested wood products created a sink of 6 to 9 million metric tons of carbon per year (Figure 17). Compared to the landfill pool, fluxes of sequestered carbon in the products-in-use fluctuated more from year to year, especially in pulpwood products because of their relatively short lifetimes. For a long run, landfills added more carbon in the accounting system with reference to annual positive carbon fluxes.

EFFECTS OF VARIOUS MANAGEMENT INTENSITIES

Regarding increasing demands of wood products, intensive management might provide opportunities for GHG mitigation. With the intensive approaches, the amount

of carbon stored in all individual pools was substantially increased. Overall, applying fertilizers and herbicide, and deploying genetically improved growing stock increased 15 percent of carbon stocks, respectively (Figure 18). However, the increased magnitudes varied among pools. The more-intensive scenario (scenario 1) produced carbon gains 20 percent in sawtimber-in-use, and 10 percent in pulpwood-in-use, landfill, and in-woods pools, respectively. For the most-intensive scenario (scenario 2), sawtimber-in-use had a 40 percent increase; pulpwood-in-use and landfill had a 25 percent increase, respectively; and in-woods had a 35 percent increase in carbon stocks by comparing to the baseline scenario. For both intensive-management scenarios, carbon stocks in sawtimber-in-use grew much faster than the other pools, primarily due to gains in volume growth that increased long-lifetime sawtimber production (Figure 19).

Beginning with applying more intensive silvicultural approaches in 2006 and following each year, southwide-level timber yield responded to such applications with a time lag at least four years (Figure 19). Use of fertilizers and herbicide enabled substantial increase in pulpwood yields from 2013 and sawtimber yields from 2010. Genetic improvements increased pulpwood yields from 2021 and sawtimber yields from 2027. As expected, with increasing yield, annual energy recapture from wood products increased 20 percent and 40 percent for the more- and most-intensive scenarios, respectively, compared to the burning wood products of 11 million metric tons of carbon per year from the base scenario (Figure 20).

DISCUSSION AND CONCLUSIONS

Regional forest carbon storage in loblolly pine plantations was modeled as an aggregate of stand-level estimates based on FIA data and FASTLOB, which served as a baseline for assessing the potential of managed extensive forests to increase carbon storage. As of 2006, aboveground carbon pools held an estimated 341 million metric tons of carbon, an amount equivalent to 20 percent of GHG emissions from energy consumed in the United States in 2006 (U.S. Environmental Protection Agency, 2008). This estimate corresponded to an average of 31 Mg of carbon accumulated on each hectare of planted loblolly pine across the South. Sources other than planted loblolly pines are excluded from these estimates. Live trees comprised 93 percent of the projected aboveground carbon, with the remaining 7 percent stored in CWD. Smith and others, (2004b) reported that carbon content in aboveground woody pools ranged between 43 and 60 $Mg \bullet ha^{-1}$ in southern loblolly-shortleaf pine forests. Their comparatively high estimates included some 45 percent natural forests, by area, compared to only plantations considered here (Forest Inventory and Analysis, 2009a). Presumably, the relatively low management intensity in natural forests allows for greater accumulations of in-woods carbon than what is accomplished in well-managed plantations. Smith and others, (2004b) also reported that CWD comprised 12 percent of in-woods carbon, an amount higher than was found here. This difference can also be attributed to differences in management intensity between their study data set and the one used here. Compared to the 11.17 million hectares of "well-managed" loblolly pine forests studied here, the FIA loblolly-shortleaf forest type comprised 25.2 million hectares of forestland (Forest Inventory and Analysis, 2009a).

Uncertainties for baseline carbon assessments were approximated by a bootstrap procedure that showed error rates of 1.40 percent for total carbon across the South and 1.27 percent for carbon mass per hectare. The relatively small sampling error rates confirm that in-woods carbon estimates from FIA survey data can be highly precise (Figure 9, Figure 10). Smith and Heath (2001) reported an error rate of 6.5 percent for carbon mass stored in aboveground softwoods of maple-beech-birch forests for area of 10^5-10^7 ha, based on growing stock used by FIA (Smith and others, 2003; Smith and others, 2004a). Bootstrap error rates for loblolly pine plantation area estimates from the same FIA data used here (details not shown) verified that the FIA-mandated maximum sampling error rate of 1.91 percent for one million hectares of forestland was not exceeded (Forest Inventory and Analysis, 2009a). These results support the widely-held understanding of bootstrap sampling as a state of the art method for quantifies uncertainty in complex statistical analyses such as the regional carbon estimates generated here.

Rotation lengths varied between 26 and 33 years for stands projected over the course of the baseline simulation, based on the targets established by the weak relationship between site index and rotation length noted in FIA data, and also accounting for target harvest levels, thinning, and the modeled age-distributions of thinning and harvesting operations over the region. Rotation lengths were generally consistent with optimal ages to harvest based on financial returns or experts' insight that final harvests occur between ages 25 and 35 years (Siry, 2002; Huang and Kronrad, 2006; Carino, 2009). Year-to-year simulated averaged ages of thinning between 17 and 20 years agreed with pulpwood harvest ages in southern pine plantations from 2000 through 2010 (Fox and others, 2004). In addition, the dip in projected annual areas for thinnings and final harvests reflected past conditions. According to Conner and Hartsell (2002), industry ownership decreased throughout the South between 1989 and 1999, to the point where the removals of growing stock in 1999 exceeded the year's annual growth. Since then the area of southern pines planted has increased, in part because of conversion of some nonforested land

area to pine plantations (Conner and Hartsell, 2002). The projected trends here reflect both the decrease in growing stock prior to 1999 and the subsequent increase reported by Conner and Hartsell (2002).

FIA initial area conditions most strongly influenced projection results during the first 30-years of the 50-year simulation period. Beyond 30 years, the assumptions embedded into the simulation, notably those assumptions related to areas managed over time, exerted stronger influence on projection results. This can be seen in the dip observed in the FIA age-class distribution (Figure 12, Figure 15) that affects areas projected to be available for thinning and final harvest, along with timber production, particularly sawtimber yields, through 2035. After 2035 projected timber production and areas harvested or thinned became relatively stable over time, presumably the result of the repeated application of modeling assumptions that fail to replicate variations that would occur under real-world conditions. In addition, the simulation assumed the area of plantation forestry will remain constant across the South for 50 years and that age distributions of growing stock and harvested wood will remain stable over time. Trends in demographics, land uses, timber supply-and-demand relationships, and timber price are all known to affect timber resources, but were deemed to be outside the scope of this study (Adams and others, 2003). The simulation methods developed here could be improved upon by accounting for future dynamics of number of planted hectares, financial returns, and individual ownerships and their associated management objectives.

Projected sawtimber yields here were lower than reported TPO values by about 35 percent. In contrast pulpwood projections matched TPO reported values almost exactly. Sawtimber output in TPO reports are derived from the loblolly-shortleaf pine forest type, which includes natural and planted pine forests with all levels of management intensity. Management goals for such forests may be considerably different than what are defined here as "well-managed" loblolly pine plantations. For example, goals may include management for aesthetics, wildlife habitat, and recreational uses for a portion of the stand's lifetime, with sawtimber harvesting taking place once economic returns become a motivating factor (Guldin, 2004). On the other hand the fact that pulpwood production results here strongly agree with TPO pulpwood production implies that loblolly pine plantations are a major source of softwood raw material for pulpwood production in the South. Challenges remain for comparing broad-scale market results such as TPO to management-oriented projections like the one conducted here.

Based on this 50-year-projection method, long-term effects of thinning and final harvest on future carbon stock in the products-in-use and landfills can be extended through 100 years or more to address the climate change issue (Miner, 2006). Projected results showed that removals in the five decades total approximately 25.7 million metric tons of carbon per year, while maintaining the region's plantation resources with a net carbon increase in growing stock over time; the harvested wood product preserves carbon with a positive flux of 6-9 million metric tons per year; an average of 11 million metric tons per year of carbon is burned for energy, equivalent to 25 percent of annual forest-products-industry renewable energy use in the United States (Perlack and others, 2005).

It has been argued that forests managed under natural conditions will store more carbon than those managed for timber production, even when carbon stored in products are accounted for (Harmon and others, 1990). For example, after a 50-year unmanaged period, all planted loblolly pine forests had quadratic mean breast height diameter of 15.5 cm, and averaged in-woods carbon mass of 115 $Mg \bullet ha^{-1}$, varying from 18 to 251 $Mg \bullet ha^{-1}$ (Figure 21A). Managed systems appear to store less carbon than their natural counterparts by means of projection (e.g. 75.3 $Mg \bullet ha^{-1}$ for the management regime and 115 $Mg \bullet ha^{-1}$ for the natural regime). Given enough time, however, carbon flux of old forests would theoretically approach zero for the rate of change of carbon accumulations (i.e. second derivative) is negative (Figure 21B). Such phenomenon in old forests is analogous to a carbon balance in planted forests between carbon captured by photosynthesis and carbon removed by thinning and final harvest. Further, wood products offer a potential advantage over manufactured materials for locking up sequestered carbon. For example, a simple sawed wood product requires 44 percent less energy consumption than steel, 93 percent less than aluminum, 60-80 percent less than concrete, or 77-83 percent less than plastic (Petersen and Solberg, 2005; Jansson and others, 2010). Managing forests to supply wood products may provide low-cost opportunities for GHG mitigation. Therefore, proper carbon mitigation policy should be a compromise between managing forests and preserving forests.

Increased demand for wood products often results in landowners adopting more intensive forest management practices (Prestemon and Abt, 2002). Management scenarios showed that through intensified application of fertilizers and herbicide and genetic improvement, improved plantation productivity increases not only the production potential of forests but also in-wood/harvested carbon stock up to 30 percent. However, fertilizers and herbicide require additional energy to produce and apply, and some of the applied fertilizers and herbicide is inevitable lost as GHG such as N_2O (Sathre and others, 2010). Such potential for lowering the GHG benefit is not accounted in management scenarios explored here.

In total, the carbon stored aboveground in loblolly pine plantations and wood harvested from them, including that used for energy production, has considerable potential to offset GHG emissions from fossil fuels. To better assess roles of such forest offset, GHG offset payments to landowners are necessary to model future market adjustments (Cairns and Lasserre, 2004; Im and others, 2007). Forestry-related policies implemented in efforts to mitigate GHG emissions or accomplish other public goals have the potential to affect landowners' management of plantation lands (Pohjola and Valsta, 2007). Despite the lack of any direct linkage to proposed public policies here, the approach used here allows for flexibility and adaptability in changing assumptions or inputs when new data and information become available. The results of projections like those presented here provide potentially useful information for use in addressing questions about the role southern pine plantations can play in GHG mitigation and climate policy.

LITERATURE CITED

Adams, D.M.; Ince, P.J.; Alig, R.J. [and others]. 2003. Assumptions and methods used in projections. In: Haynes, R.W. (Ed.), An Analysis of the Timber Situation in the United States: 1952 to 2050. Gen. Tech. Rep. PNW-GTR-560 USDA Forest Service, Pacific Northwest Research Station, Portland, OR. p. 10-54.

Albaugh, T.J.; Allen, H.L.; Fox, T.R. 2007. Historical patterns of forest fertilization in the southeastern United States from 1969 to 2004. Southern Journal of Applied Forestry 31 (3), 129-137.

Allen, H.L. 2001. Silvicultural treatments to enhance productivity. In: Evans, J. (Ed.), The Forests Handbook. Volume II. Blackwell Science Ltd., Oxford, UK.

Allen, H.L.; Fox, T.R.; Campbell, R.G. 2005. What is ahead for intensive pine plantation silviculture in the south? Southern Journal of Applied Forestry 29 (2), 62-69.

Amateis, R.L.; Burkhart, H.E. 1996. Impact of heavy glaze in a loblolly pine spacing trial. Southern Journal of Applied Forestry 20 (3), 151-155.

Amateis, R.L.; Burkhart, H.E. 2005. The influence of thinning on the proportion of peeler, sawtimber, and pulpwood trees in loblolly pine plantations. Southern Journal of Applied Forestry 29 (3), 158-162.

Amateis, R.L.; Burkhart, H.E. 2009. FASTLOB 3.0: A Stand-level Growth and Yield Model for Fertilized and thinned Loblolly Pine Plantations The Loblolly Pine Growth and Yield Research Cooperative, Department of Forestry, Virginia Tech, Blacksburg, Virginia, p. 38.

Applegate, J.R. 2008. Estimates of down woody materials on Fort AP Hill, Virginia. Southern Journal of Applied Forestry 32 (2), 53-59.

Baldwin, V.C.; Peterson, K.D.; Burkhart, H.E. [and others]. 1997. Equations for estimating loblolly pine branch and foliage weight and surface area distributions. Canadian Journal of Forest Research 27 (6), 918-927.

Baskerville, G.L. 1972. Use of logarithmic regression in the estimation of plant biomass. Canadian Journal of Forest Research 2, 49-53.

Bechtold, W.A.; Scott, C.T. 2005. The Forest Inventory and Analysis plot design. In: Bechtold, W.A., Patterson, P.L. (Eds.), The enhanced Forest Inventory and Analysis program - National sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. USDA Forest Service, Southern Research Station, Ashevill, NC, pp. 27-42.

Birdsey, R.A.; Heath, L.S. 1995. Carbon Changes in U.S. Forests. In: Joyce, L.A. (Ed.), Productivity of America's Forests and Climate Change. Gen. Tech. Rep. RM-GTR-271. USDA Forest Service, Rocky Mountain Forest Experiment Station, Fort Collins, CO, pp. 56-70.

Booth, J.G.; Sarkar, S. 1998. Monte Carlo approximation of bootstrap variances. American Statistician 52 (4), 354-357.

Bullock, B.P.; Burkhart, H.E. 2003. Equations for predicting green weight of loblolly pine trees in the South. Southern Journal of Applied Forestry 27 (3), 153-159.

Cairns, R.D.; Lasserre, P. 2004. Reinforcing economic incentives for carbon credits for forests. Forest Policy and Economics 6 (3-4), 321-328.

Campbell, J.W.; Hanula, J.L.; Outcalt, K.W. 2008. Effects of prescribed fire and other plant community restoration treatments on tree mortality, bark beetles, and other saproxylic Coleoptera of longleaf pine, Pinus palustris Mill., on the Coastal Plain of Alabama. Forest Ecology and Management 254 (2), 134-144.

Carino, H.F. 2009. Maximizing the value yield of short-rotation southern pine timber. Forest Products Journal 59 (9), 29-37.

Chojnacky, D.C.; Heath, L.S. 2002. Estimating down deadwood from FIA forest inventory variables in Maine. Environmental Pollution 116, S25-S30.

Chojnacky, D.C.; Schuler, T.M. 2004. Amounts of down woody materials for mixed-oak forests in Kentucky, Virginia, Tennessee, and North Carolina. Southern Journal of Applied Forestry 28 (2), 113-117.

Clutter, J.L.; Fortson, J.C.; Pienaar, L.V. [and others]. 1983. Timber management : a quantitative approach. Wiley, New York,

Conner, R.C.; Hartsell, A.J. 2002. Forest area and conditions. In: Wear, D.N., Greis, J.G. (Eds.), Southern Forest Resource Assessment. GTR SRS-53. USDA Forest Service, Southern Research Station, Asheville, NC, pp. 357-402.

Cooper, J.; Becker, C. 2009. Virginia's timber industry--an assessment of timber product output and use, 2007. Resour. Bull. SRS--155. USDA Forest Service, Southern Research Station, Asheville, NC, p. 33.

Duvall, M.D.; Grigal, D.F. 1999. Effects of timber harvesting on coarse woody debris in red pine forests across the Great Lakes states, USA. Canadian Journal of Forest Research 29 (12), 1926-1934.

Ekbom, B.; Schroeder, L.M.; Larsson, S. 2006. Stand specific occurrence of coarse woody debris in a managed boreal forest landscape in central Sweden. Forest Ecology and Management 221 (1-3), 2-12.

Forest Inventory and Analysis. 2007. Forest Inventory and Analysis Factsheet, Virginia, USDA Forest Service, Forest Inventory and Analysis, Southern Research Station, Knoxville TN, http://srsfia2.fs.fed.us/states/virginia.shtml. Date Accessed: 05/10/2009.

Forest Inventory and Analysis. 2009a. FIA DataMart - FIADB version 4.0, USDA Forest Service, Forest Inventory and Analysis National Program, Arlington VA, http://fiatools.fs.fed.us/fiadb-downloads/datamart.html. Date Accessed: 06/05/2009.

Forest Inventory and Analysis. 2009b. FIA Field Guide, USDA Forest Service, Forest Inventory and Analysis National Program, Arlington VA, http://fia.fs.fed.us/library/field-guides-methods-proc/. Date Accessed: 04/12/2010.

Fox, T.R.; Allen, H.L.; Albaugh, T.J. [and others]. 2007. Tree nutrition and forest fertilization of pine plantations in the southern United States. Southern Journal of Applied Forestry 31 (1), 5-11.

Fox, T.R.; Jokela, E.J.; Allen, H.L. 2004. The evolution of pine plantation silviculture in the southern United States. In: Rauscher, H.M., Johnsen, K. (Eds.), Southern Forest Science: Past, Present, and Future. Gen. Tech. Rep. SRS–75. USDA, Forest Service, Southern Research Station, Asheville, NC, pp. 63-82.

Freese, F. 1967. Elementary statistical methods for foresters. Agricultural Handbook 317. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, pp. 5-6.

Fridman, J.; Walheim, M. 2000. Amount, structure, and dynamics of dead wood on managed forestland in Sweden. Forest Ecology and Management 131 (1-3), 23-36.

Gibson, M.D.; McMillin, C.W.; Shoulders, E. 1986. Moisture content and specific gravity of the four major southern pines under the same age and site conditions. Wood and Fiber Science 18 (3), 428-435.

Glass, S.V.; Zelinka, S.L. 2010. Moisture relations and physical properties of wood. Wood Handbook, Wood as an Engineering Material. General Technical Report FPL-GTR-190. USDA Forest Service, Forest Products Laboratory, Madison, WI, pp. 4-1 - 4-19.

Gong, P.C. 1998. Risk preferences and adaptive harvest policies for even-aged stand management. Forest Science 44 (4), 496-506.

Guldin, J.M. 2004. Reproduction cutting methods for naturally regenrated pine stands in the South. In: Rauscher, H.M., Johnsen, K. (Eds.), Southern Forest Science: Past, Present, and Future. Gen. Tech. Rep. SRS–75. USDA, Forest Service, Southern Research Station, Asheville, NC, pp. 83-95.

Harmon, M.E. 2001. Carbon sequestration in forests - Addressing the scale question. Journal of Forestry 99 (4), 24-29.

Harmon, M.E.; Ferrell, W.K.; Franklin, J.F. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247 (4943), 699-702.

Heath, L.S.; Smith, J.E. 2004. Criterion 5, Indicator 27: contribution of forest ecosystems to the total global carbon budget, including absorption and release of carbon. In: Darr, D.R. (Ed.), Data Report: A Supplement of the National Report on Sustainable Forests--2003. FS-766A. USDA, Washington, DC, p. 7.

Heath, L.S.; Smith, J.E.; Birdsey, R.A. 2003. Carbon trends in U.S. forestlands: a context for the role of soils in forest carbon sequestration. In: Kimble, J.M., Heath, L.S., Birdsey, R.A., Lal, R. (Eds.), The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. CRC Press, Boca Raton, pp. 35-45.

Herrmann, S.; Prescott, C.E. 2008. Mass loss and nutrient dynamics of coarse woody debris in three Rocky Mountain coniferous forests: 21 year results. Canadian Journal of Forest Research 38 (1), 125-132.

Houghton, R.A.; Hackler, J.L.; Lawrence, K.T. 1999. The US carbon budget: Contributions from land-use change. Science 285 (5427), 574-578.

Huang, C.H.; Kronrad, G.D. 2006. The effect of carbon revenues on the rotation and profitability of loblolly pine plantations in East Texas. Southern Journal of Applied Forestry 30 (1), 21-29.

Im, E.H.; Adams, D.M.; Latta, G.S. 2007. Potential impacts of carbon taxes on carbon flux in western Oregon private forests. Forest Policy and Economics 9 (8), 1006-1017.

Janssens, I.A.; Freibauer, A.; Ciais, P. [and others]. 2003. Europe's terrestrial biosphere absorbs 7 to 12 percent of European anthropogenic CO2 emissions. Science 300 (5625), 1538-1542.

Jansson, C.; Wullschleger, S.D.; Kalluri, U.C.; Tuskan, G.A. 2010. Phytosequestration: Carbon biosequestration by plants and the prospects of genetic engineering. Bioscience 60 (9), 685-696.

Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. 2003. National-scale biomass estimators for United States tree species. Forest Science 49 (1), 12-35.

Johnsen, K.H.; Wear, D.; Oren, R. [and others]. 2001. Carbon sequestration and southern pine forests. Journal of Forestry 99 (4), 14-21.

Johnson, T.G.; Steppleton, C.D.; Bentley, J.W. 2010. Southern pulpwood production, 2008. Resour. Bull. SRS–165. USDA Forest Service, Southern Research Station, Asheville, NC, p. 42.

Jokela, E.J.; Dougherty, P.M.; Martin, T.A. 2004. Production dynamics of intensively managed loblolly pine stands in the southern United States: a synthesis of seven long-term experiments. Forest Ecology and Management 192 (1), 117-130.

Kangas, A.S. 1997. On the prediction bias and variance in long-term growth projections. Forest Ecology and Management 96 (3), 207-216.

Krankina, O.N.; Harmon, M.E.; Griazkin, A.V. 1999. Nutrient stores and dynamics of woody detritus in a boreal forest: modeling potential implications at the stand level. Canadian Journal of Forest Research 29 (1), 20-32.

Krankina, O.N.; Harmon, M.E.; Kukuev, Y.A. [and others]. 2002. Coarse woody debris in forest regions of Russia. Canadian Journal of Forest Research 32 (5), 768-778.

Landsberg, J.J.; Waring, R.H. 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 95 (3), 209-228.

Li, B.; McKeand, S.; Weir, R. 1999. Impact of Forest Genetics on Sustainable Forestry—Results from Two Cycles of Loblolly Pine Breeding in the U.S. Journal of Sustainable Forestry 10 (1-2), 79-85.

Liechty, H.O.; Fristoe, C. 2010. Initial response of loblolly pine and competition to mid rotation fertilization and herbicide application in the gulf coastal plain. In: Stanturf, J.A. (Ed.), Proceedings of the 14th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–121. USDA, Forest Service, Southern Research Station, Asheville, NC, pp. 47-49.

Little, E.L. 1971. Atlas of United States Trees, Volume 1, Conifers and Important Hardwoods. USDA Miscellaneous Publication 1146, 9 p., 200 maps, http://esp.cr.usgs.gov/data/atlas/little/. Date Accessed: 7/15/2009.

Marra, J.L.; Edmonds, R.L. 1994. Coarse woody debris and forest floor respiration in an old-growth coniferous forest on the Olympic Peninsula, Washington, USA. Canadian Journal of Forest Research 24 (9), 1811-1817.

McKeand, S.; Mullin, T.; Byram, T.; White, T. 2003. Deployment of genetically improved loblolly and slash pines in the south. Journal of Forestry 101 (3), 32-37.

McKeand, S.E.; Abt, R.C.; Allen, H.L. [and others]. 2006. What are the best loblolly pine genotypes worth to landowners? Journal of Forestry 104 (7), 352-358.

McKenney, D.W.; Yemshanov, D.; Fox, G.; Ramlal, E. 2004. Cost estimates for carbon sequestration from fast growing poplar plantations in Canada. Forest Policy and Economics 6 (3-4), 345-358.

McMinn, J.W.; Crossley, D.A. 1996. Biodiversity and Coarse Woody Debris in Southern Forests. Gen. Tech. Rep. SE-94. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC, p. 146.

McMinn, J.W.; Hardt, R.A. 1996. Accumulations of coarse woody debris in Southern forests. In: McMinn, J.W., Crossley, D.A. (Eds.), Biodiversity and Coarse Woody Debris in Southern Forests. Gen. Tech. Rep. SE-94. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC, pp. 1-9.

Miller, A.T.; Allen, H.L.; Maier, C.A. 2006. Quantifying the coarse-root biomass of intensively managed loblolly pine plantations. Canadian Journal of Forest Research 36 (1), 12-22.

Miner, R. 2006. The 100-year method for forecasting carbon sequestration in forest products in use. Mitigation and Adaptation Strategies for Global Change(online http://www.springerlink.com/content/2l67274117366751/).

Morris, L.A.; Lowery, R.F. 1988. Influence of site preparation on soil conditions affecting stand establishment and tree growth. Southern Journal of Applied Forestry 12 (3), 170-178.

Moulton, R.J.; Hernandez, G. 2000. Tree planting in the United States - 1998. Tree Planters' Notes 49 (2), 23-36.

Nilsson, U.; Allen, H.L. 2003. Short- and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. Forest Ecology and Management 175 (1-3), 367-377.

Oswalt, S.N.; Oswalt, C.; Turner, J. 2008. Hurricane Katrina impacts on Mississippi forests. Southern Journal of Applied Forestry 32 (3), 139-141.

Pacala, S.W.; Hurtt, G.C.; Baker, D. [and others]. 2001. Consistent land- and atmosphere-based US carbon sink estimates. Science 292 (5525), 2316-2320.

Page-Dumroese, D.S.; Jurgensen, M.F. 2006. Soil carbon and nitrogen pools in mid- to late-successional forest stands of the northwestern United States: potential impact of fire. Canadian Journal of Forest Research 36 (9), 2270-2284.

Perez-Garcia, J.; Lippke, B.; Comnick, J.; Manriquez, C. 2005. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. Wood and Fiber Science 37, 140-148.

Perlack, R.D.; Wright, L.L.; Turhollow, A.F. [and others]. 2005. Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. DOE/USDA Tech. Rep. DOE/GO-102005–2135. USDOE, Office of Scientific & Technical Information, Oak Ridge, TN, p. 78.

Petersen, A.K.; Solberg, B. 2005. Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. Forest Policy and Economics 7 (3), 249-259.

Pohjola, J.; Valsta, L. 2007. Carbon credits and management of Scots pine and Norway spruce stands in Finland. Forest Policy and Economics 9 (7), 789-798.

Prestemon, J.P.; Abt, R.C. 2002. The Southern timber market to 2040. Journal of Forestry 100 (7), 16-22.

Price, T.; Doggett, C.; Pye, J.; Smith, B. 1998. A History of Southern Pine Beetle Outbreaks in the Southeastern United States. Georgia Forestry Commission, Atlanta, GA,

Radtke, P.J.; Amateis, R.L.; Prisley, S.P. [and others]. 2009. Modeling production and decay of coarse woody debris in loblolly pine plantations. Forest Ecology and Management 257 (3), 790-799.

Reams, G.A.; Smith, W.D.; Hansen, M.H. [and others]. 2005. The Forest Inventory and Analysis sampling frame. In: Bechtold, W.A., Patterson, P.L. (Eds.), The enhanced Forest Inventory and Analysis program - National sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. USDA Forest Service, Southern Research Station, Ashevill, NC, pp. 11-26.

Rubino, D.L.; McCarthy, B.C. 2003. Evaluation of coarse woody debris and forest vegetation across topographic gradients in a southern Ohio forest. Forest Ecology and Management 183 (1-3), 221-238.

Sathre, R.; Gustavsson, L.; Bergh, J. 2010. Primary energy and greenhouse gas implications of increasing biomass production through forest fertilization. Biomass & Bioenergy 34 (4), 572-581.

Schiermeier, Q.; Tollefson, J.; Scully, T. [and others]. 2008. Electricity without carbon. Nature 454 (7206), 816-823.

Schimel, D.; Melillo, J.; Tian, H.Q. [and others]. 2000. Contribution of increasing CO2 and climate to carbon storage by ecosystems in the United States. Science 287 (5460), 2004-2006.

Schultz, R.P. 1997. Loblolly Pine: The Ecology and Culture of Loblolly Pine (Pinus taeda L.). Agriculture Handbook 713. USDA Forest Service, Washington, D.C., p. 493.

Schulze, E.D.; Wirth, C.; Heimann, M. 2000. Climate change - managing forests after Kyoto. Science 289 (5487), 2058-2059.

Scott, C.T.; Bechtold, W.A.; Reams, G.A. [and others]. 2005. Sample-based estimators used by the Forest Inventory and Analysis National Information Management System. In: Bechtold, W.A., Patterson, P.L. (Eds.), The Enhanced Forest Inventory and Analysis Program - National Sampling Design and Estimation Procedures. Gen. Tech. Rep. SRS-80 USDA Forest Service, Southern Research Station, Ashevill, NC, pp. 43-67.

Siry, J.P. 2002. Intensive timber management practices. In: Wear, D.N., Greis, J.G. (Eds.), Southern Forest Resource Assessment. GTR SRS-53. USDA Forest Service, Southern Research Station, Asheville, NC, pp. 327-340.

Siry, J.P.; Cubbage, F.W.; Malmquist, A.J. 2001. Potential impacts of increased management intensities on planted pine growth and yield and timber supply modeling in the south. Forest Products Journal 51 (3), 42-48.

Skog, K.E.; Nicholson, G.A. 1998. Carbon cycling through wood products: The role of wood and paper products in carbon sequestration. Forest Products Journal 48 (7-8), 75-83.

Smith, J.E.; Heath, L.S. 2001. Identifying influences on model uncertainty: An application using a forest carbon budget model. Environmental Management 27 (2), 253-267.

Smith, J.E.; Heath, L.S. 2002. A model of forest floor carbon mass for United States forest types. Res. Pap. NE-722. USDA Forest Service, Northeastern Research Station, Newtown Square, PA, p. 37.

Smith, J.E.; Heath, L.S.; Jenkins, J.C. 2003. Forest Volume-to-Biomass Models and Estimates of Mass for Live and Standing Dead Trees of U.S. Forests. Gen. Tech. Rep. NE-298. USDA Forest Service, Northeastern Research Station, Newtown Square, PA, p. 57.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. USDA Forest Service, Northeastern Research Station, Newtown Square, PA, p. 216.

Smith, J.E.; Heath, L.S.; Woodbury, P.B. 2004a. How to estimate forest carbon for large areas from inventory data. Journal of Forestry 102 (5), 25-31.

Smith, J.E.; Heath, L.S.; Woodbury, P.B. 2004b. How to estimate forest carbon for large areas from inventory data- Supplemental material for Tables 1 and 2 http://www.forestcarbon.net/ Date Accessed: 12/08/2010.

Smith, W.B. 2002. Forest inventory and analysis: a national inventory and monitoring program. Environmental Pollution 116, S233-S242.

Smith, W.B.; Miles, P.D.; Vissage, J.S.; Pugh, S.A. 2004c. Forest Resources of the United States, 2002. Gen. Tech. Rep. NC-241 USDA Forest Service, North Central Research Station, St. Paul, MN, p. 137.

Spetich, M.A.; Shifley, S.R.; Parker, G.R. 1999. Regional distribution and dynamics of coarse woody debris in midwestern old-growth forests. Forest Science 45 (2), 302-313.

Spies, T.A.; Franklin, J.F.; Thomas, T.B. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology 69 (6), 1689-1702.

U.S. Energy Information Administration. 2010. Biomass for Electricity Generation, http://www.eia.doe.gov/oiaf/analysispaper/biomass/table3.html. Date Accessed: 11/18/2010.

U.S. Environmental Protection Agency. 2007a. Clean Air Markets Division data and maps, http://camddataandmaps.epa.gov/gdm/. Date Accessed: 02/16/2009.

U.S. Environmental Protection Agency. 2007b. Clean Air Markets Division data and maps web site, http://camddataandmaps.epa.gov/gdm/. Date Accessed: 02/16/2009

U.S. Environmental Protection Agency. 2008. Inventory of U.S. greenhouse gas emissions and sinks: 1990 - 2006. EPA 430-R-08-005. Office of Atmospheric Programs, Washington, DC.

Vanderwel, M.C.; Thorpe, H.C.; Shuter, J.L. [and others]. 2008. Contrasting downed woody debris dynamics in managed and unmanaged northern hardwood stands. Canadian Journal of Forest Research 38 (11), 2850-2861.

Wade, D.D. 1993. Thinning young loblolly pine stands with fire. International Journal of Wildland Fire 3 (3), 169-178.

Wear, D.N.; Greis, J.G. 2002. Southern Forest Resource Assessment - Technical Report. GTR SRS-53. USDA Forest Service, Southern Research Station, Asheville, NC, p. 635.

Woodall, C.W.; Monleon, V.J. 2008. Sampling Protocol, Estimation, and Analysis Procedures for the Down Woody Materials Indicator of the FIA Program. Gen. Tech. Rep. NRS-22. USDA Forest Service, Northern Research Station, Newtown Square, PA, p. 72.

Table 1—Summary of stand attributes (area-weighted mean) for FIA sampled field plots and their representative forestland area of loblolly pine plantations by southern States

State	Plots	Area	SI†	Planting	Age	TPA	BA‡	Thinning	
		(10^6 ha)	(m)	(seedlings·ha^{-1})	(yrs)	(trees·ha^{-1})	(m^2·ha^{-1})	Age	TPA
Alabama	976	1.95	20.0	1,040	14	867	13.8	19	425
Arkansas	406	0.85	17.0	1,127	18	788	15.8	24	413
Florida	116	0.24	19.7	1,095	16	912	14.9	-	-
Georgia	833	1.66	19.8	941	16	870	14.2	20	390
Louisiana	508	1.09	19.7	1,038	14	964	14.2	23	467
Mississippi	823	1.63	19.8	1,080	15	833	14.9	21	445
North Carolina	394	1.00	18.5	1,191	19	818	15.6	24	319
South Carolina	575	1.10	19.6	1,240	17	855	16.1	21	405
Tennessee	83	0.15	18.5	751	14	754	11.5	20	425
Texas	437	0.87	19.1	1,176	14	843	12.6	18	415
Virginia	329	0.63	18.5	1,038	19	813	15.4	24	334
South	5,480	11.17	19.4	1,067	16	855	14.7	21	410

† Site index at base age of 25 years
‡ Basal area

Table 2—State-level and southwide in-woods carbon mass totals (10^6 Mg) and means (Mg·ha^{-1}): FIA estimates and bootstrap standard errors and 95 percent confidence intervals

State	In-woods carbon total (10^6 Mg)				In-woods carbon mean (Mg·ha^{-1})			
	Estimate†	SE‡ (%)	95% CI		Estimate†	SE‡ (%)	95% CI	
			2.5th	97.5th			2.5th	97.5th
Alabama	53.7	4.21	49.4	58.2	27.49	2.74	26.02	28.89
Arkansas	26.7	7.12	23.2	30.7	31.43	4.69	28.69	34.39
Florida	7.2	12.35	5.5	9.1	30.25	7.70	25.76	34.98
Georgia	49.4	4.50	45.1	53.8	29.83	2.86	28.19	31.55
Louisiana	31.2	6.89	27.1	35.4	28.58	5.33	25.67	31.59
Mississippi	52.5	4.52	47.9	57.2	32.11	2.90	30.28	33.91
North Carolina	35.4	6.73	30.7	40.3	35.51	4.36	32.48	38.53
South Carolina	38.5	5.58	34.4	42.8	34.97	3.42	32.66	37.20
Tennessee	3.3	18.15	2.2	4.5	21.30	12.94	15.84	26.69
Texas	21.4	6.78	18.6	24.2	24.52	4.66	22.43	26.86
Virginia	22.1	7.71	18.7	25.4	34.99	4.75	31.74	38.15
South	341.1	1.40	331.7	350.5	30.54	1.27	29.77	31.31

† Estimate based on FIA 2005—2007 data and FASTLOB yield predictions
‡ Estimated standard error from bootstrap sampling

Table 3—State-level and southwide live-tree carbon mass totals (10^6 Mg) and means (Mg·ha^{-1}): FIA estimates and bootstrap standard errors and 95 percent confidence intervals

State	Live-tree carbon total (10^6 Mg)				Live-tree carbon mean (Mg·ha^{-1})			
	Estimate†	SE‡ (%)	95% CI		Estimate†	SE‡ (%)	95% CI	
			2.5th	97.5th			2.5th	97.5th
Alabama	50.5	4.19	46.5	54.7	25.85	2.71	24.46	27.17
Arkansas	24.6	6.88	21.4	28.0	28.96	4.36	26.56	31.50
Florida	6.8	12.36	5.2	8.6	28.62	7.70	24.33	33.08
Georgia	46.8	4.49	42.7	50.8	28.22	2.82	26.64	29.82
Louisiana	28.5	6.62	24.9	32.1	26.11	4.93	23.70	28.65
Mississippi	49.5	4.49	45.1	53.8	30.28	2.84	28.58	31.95
North Carolina	31.3	6.47	27.3	35.5	31.35	3.94	28.99	33.71
South Carolina	36.1	5.59	32.2	40.2	32.78	3.41	30.57	34.90
Tennessee	3.0	18.17	2.0	4.1	19.53	12.92	14.50	24.52
Texas	19.9	6.65	17.3	22.5	22.81	4.45	20.97	24.83
Virginia	19.7	7.51	16.8	22.6	31.28	4.42	28.57	33.91
South	316.4	1.35	308.1	324.7	28.32	1.22	27.63	29.00

† Estimate based on FIA 2005—2007 data and FASTLOB yield predictions
‡ Estimated standard error from bootstrap sampling

Table 4—State-level and southwide CWD carbon mass totals (10^6 Mg) and means (Mg·ha^{-1}): FIA estimates and bootstrap standard errors and 95 percent confidence intervals

State	CWD carbon total (10^6 Mg)				CWD carbon mean (Mg·ha^{-1})			
	Estimate†	SE‡ (%)	95% CI		Estimate†	SE‡ (%)	95% CI	
			2.5th	97.5th			2.5th	97.5th
Alabama	3.2	8.59	2.7	3.8	1.65	8.01	1.39	1.91
Arkansas	2.1	15.16	1.6	2.8	2.47	13.99	1.87	3.20
Florida	0.4	15.94	0.3	0.5	1.63	12.86	1.24	2.06
Georgia	2.7	6.90	2.4	3.1	1.61	6.11	1.44	1.81
Louisiana	2.7	15.23	2.0	3.6	2.47	14.75	1.81	3.24
Mississippi	3.0	7.17	2.6	3.4	1.83	6.35	1.61	2.07
North Carolina	4.2	13.30	3.2	5.4	4.16	12.31	3.27	5.29
South Carolina	2.4	7.56	2.1	2.8	2.19	6.38	1.91	2.46
Tennessee	0.3	32.96	0.1	0.5	1.77	30.62	0.84	2.89
Texas	1.5	13.49	1.1	1.9	1.71	12.65	1.31	2.16
Virginia	2.4	14.69	1.8	3.1	3.71	13.36	2.83	4.77
South	24.7	3.69	23.0	26.5	2.21	3.65	2.06	2.38

† Estimate based on FIA 2005—2007 data and FASTLOB yield predictions
‡ Estimated standard error from bootstrap sampling

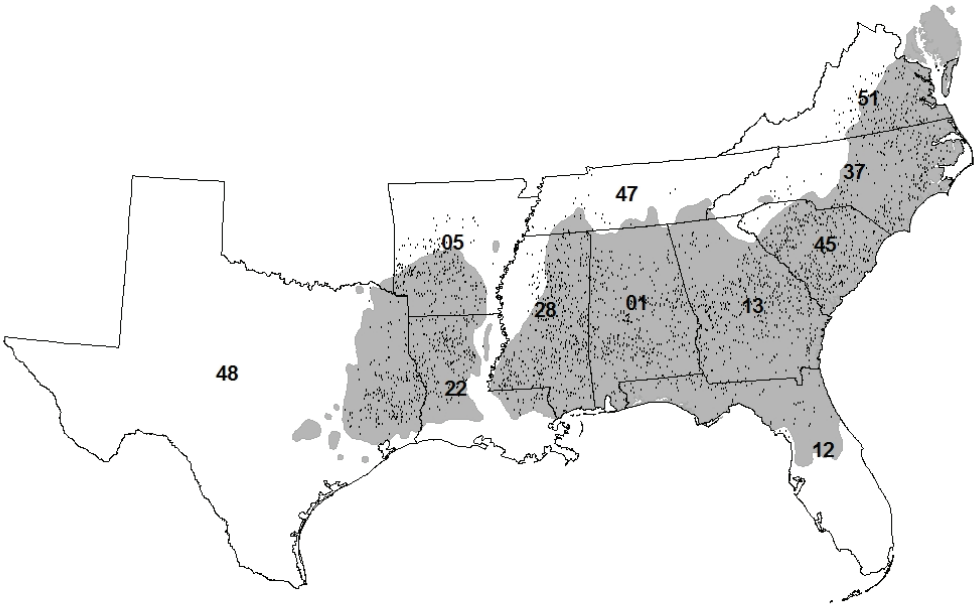

Figure 1. Approximate Forest Inventory and Analysis (FIA) plot locations for loblolly pine plantations and the natural range† of loblolly pine forests (shaded) in the southern United States. State codes – 01: Alabama, 05: Arkansas, 12: Florida, 13: Georgia, 22: Louisiana, 28: Mississippi, 37: North Carolina, 45: South Carolina, 47: Tennessee, 48: Texas, and 51: Virginia.
† Geographic distribution of loblolly pine is obtained from Little (1971).

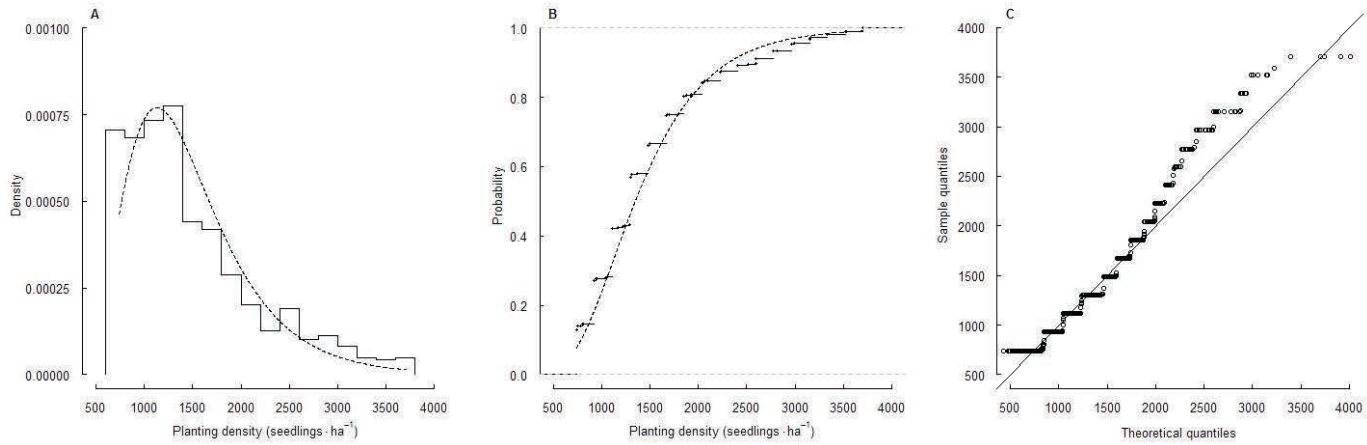

Figure 2—Fitted log-normal distribution of planting density (μ = 7.21, σ = 0.42, while the variable at natural logarithm scale): (A) Histogram of observed data versus fundamental shape; (B) Empirical versus theoretical cumulative distribution functions (ECDF versus CDF) (C) Empirical quantiles versus theoretical quantiles from a log-normal distribution.

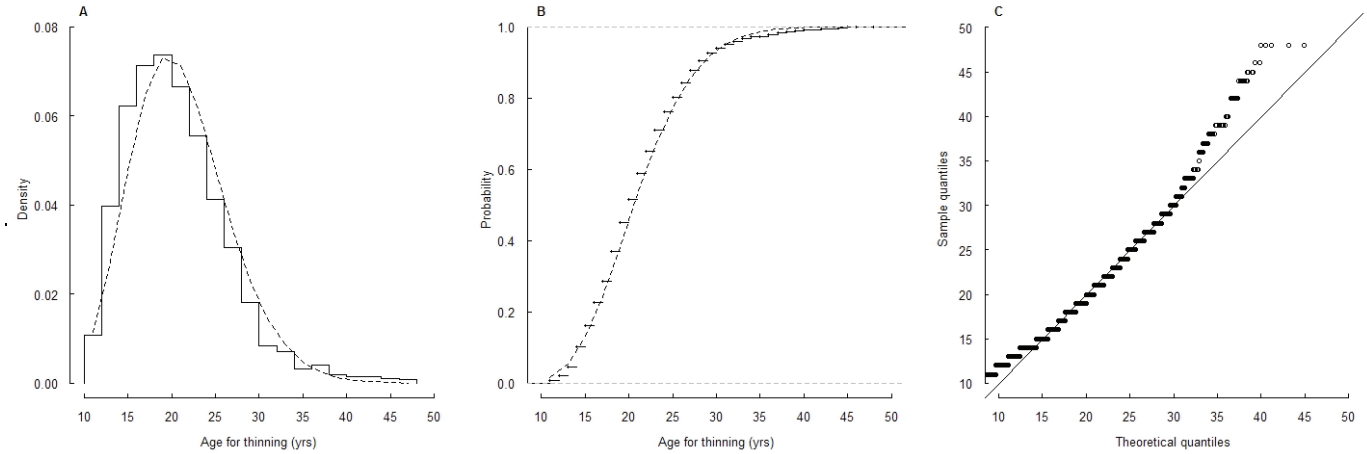

Figure 3—Fitted gamma distribution of age of thinning (α = 14.31, λ= 0.68): (A) Histogram of observed data and fitted gamma density function; (B) ECDF versus CDF; (C) Empirical quantiles versus theoretical quantiles from a gamma distribution.

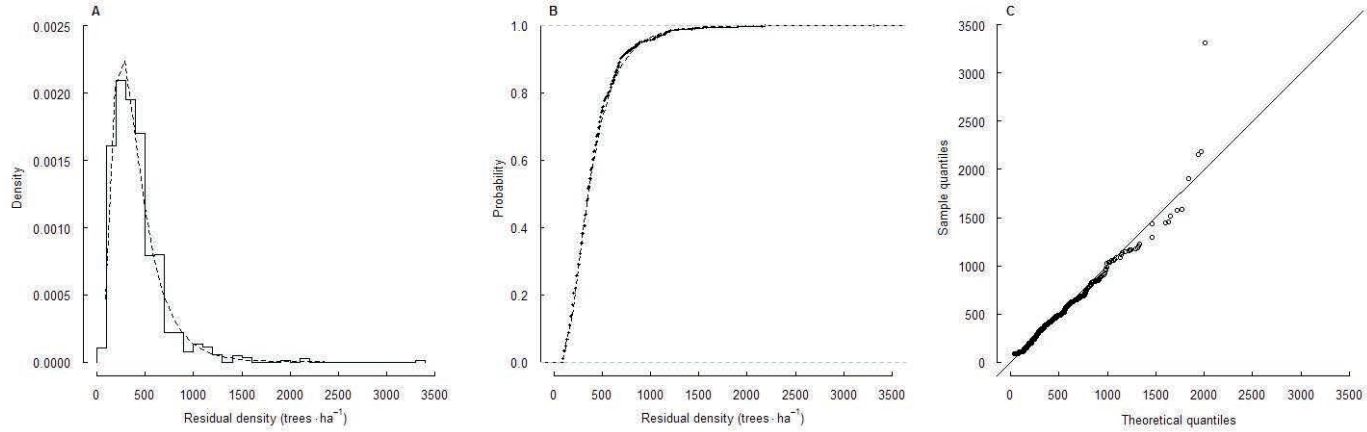

Figure 4—Fitted log-normal distribution of residual density after thinning (μ = 5.86, σ = 0.58, while the variable at natural logarithm scale): (A) Histogram of observed data and fitted lognormal function; (B) ECDF versus CDF (C) Empirical quantiles versus theoretical quantiles from a log-normal distribution.

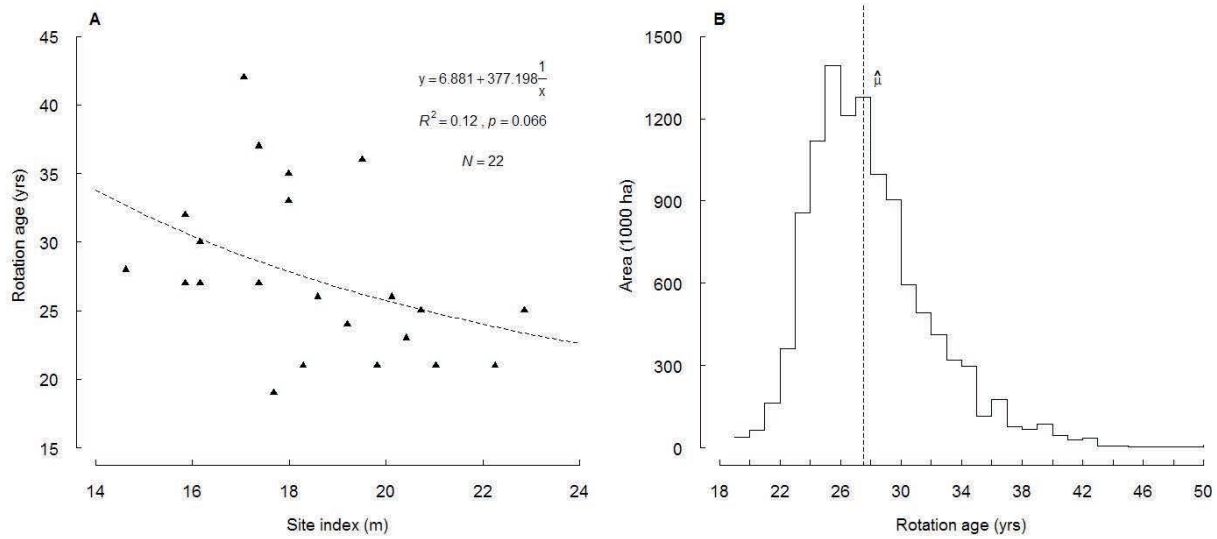

Figure 5—Distribution of rotation ages, accounting for site index at base age 25: (A) The relationship between FIA observed rotation ages and site index; (B) Predicted rotation ages for all stands across the South with a mean $\hat{\mu} = 27.5$

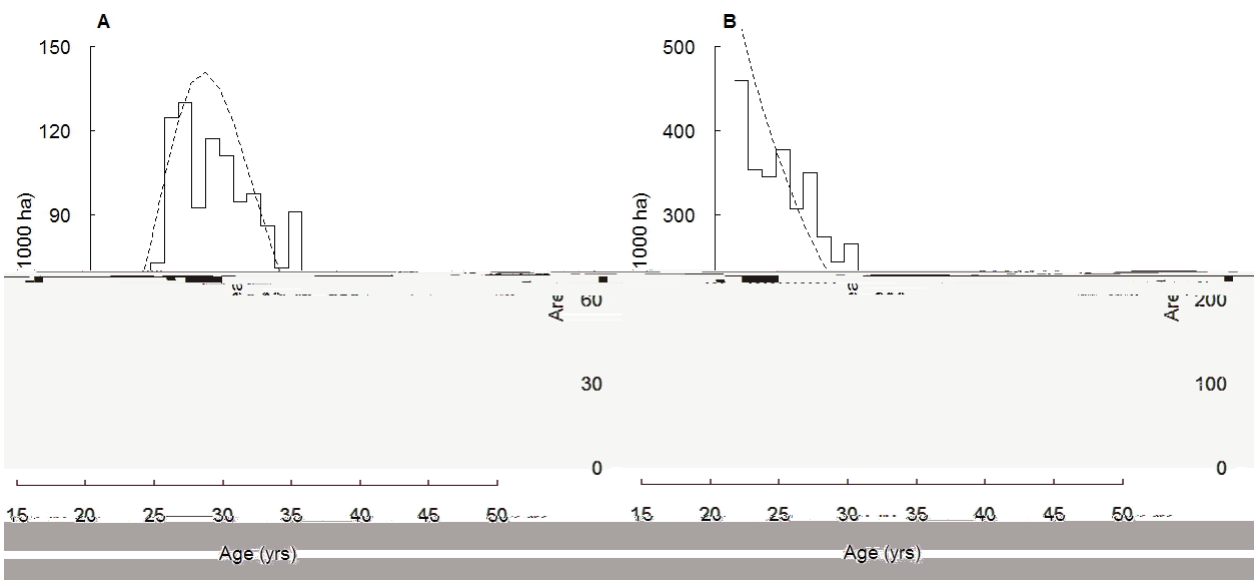

Figure 6—Quality of fit for distributions of planted area by age classes throughout the South (A) Stands with evidence of thinning which age class at 22 yrs has largest fitted area; (B) Stands without thinning observed which age class at 16 yrs has largest fitted area.

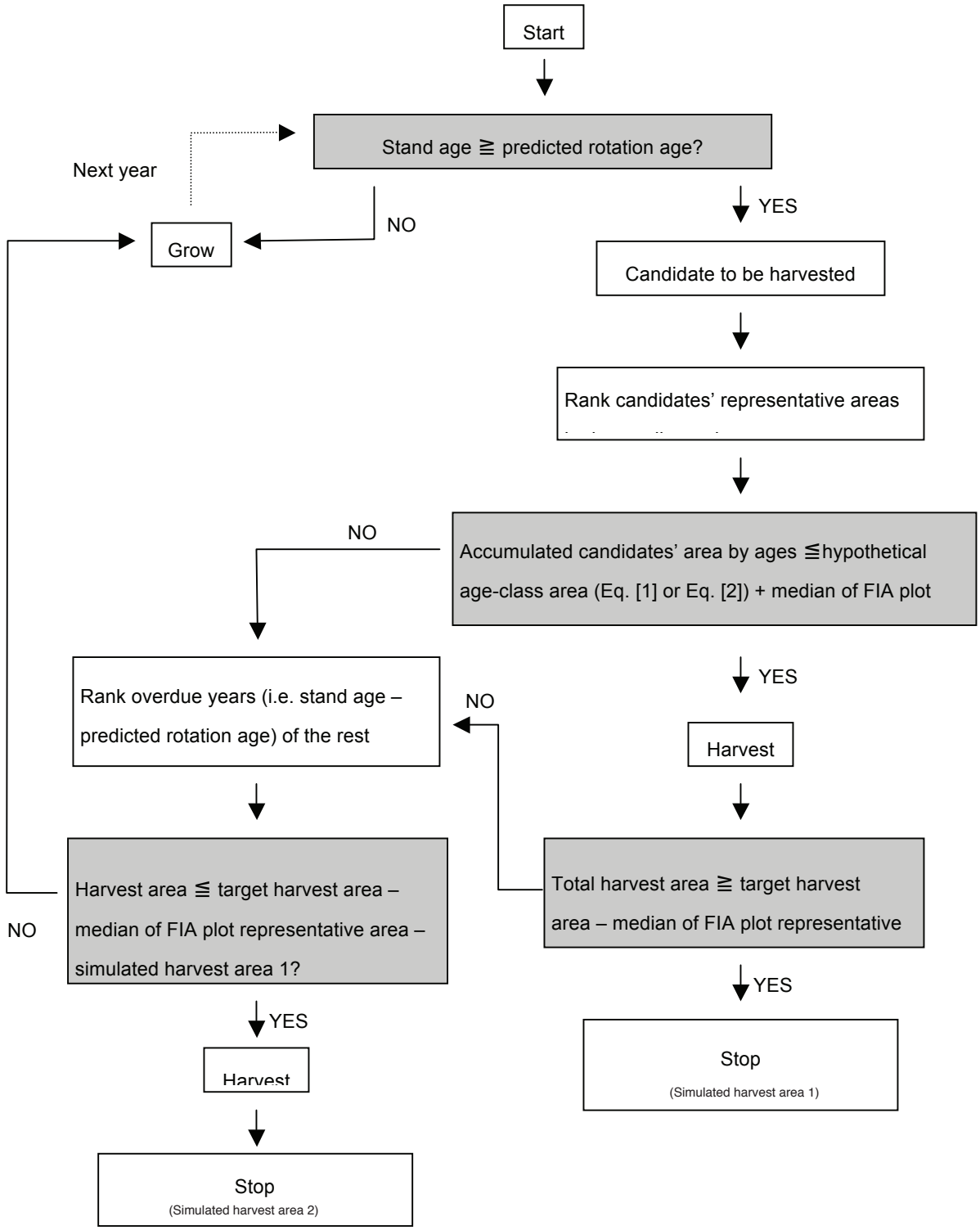

Figure 7—Rules used to select FIA plots for harvesting from thinned [1] and never-thinned [2] plantations.

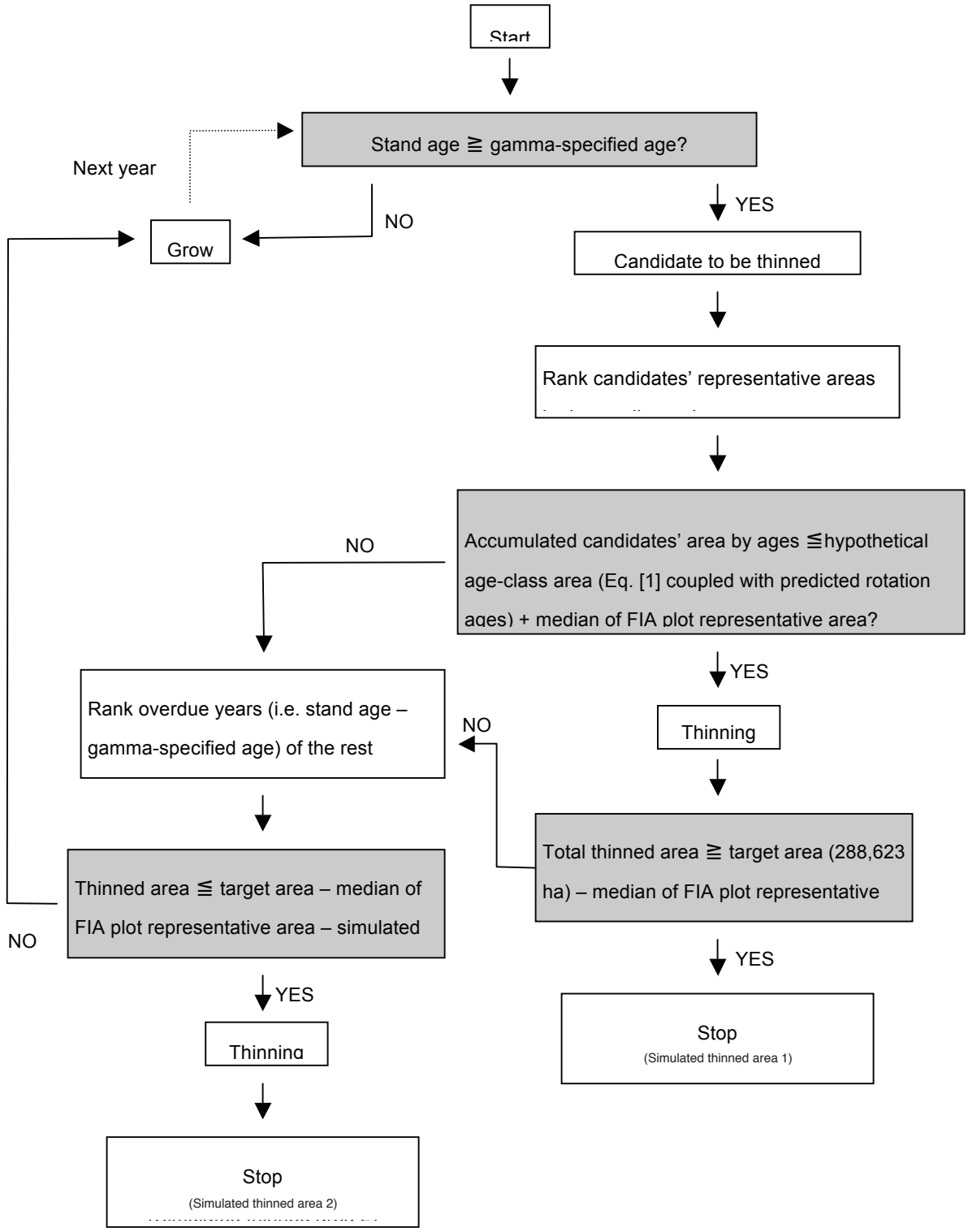

Figure 8—Rules used to select FIA plots for thinning.

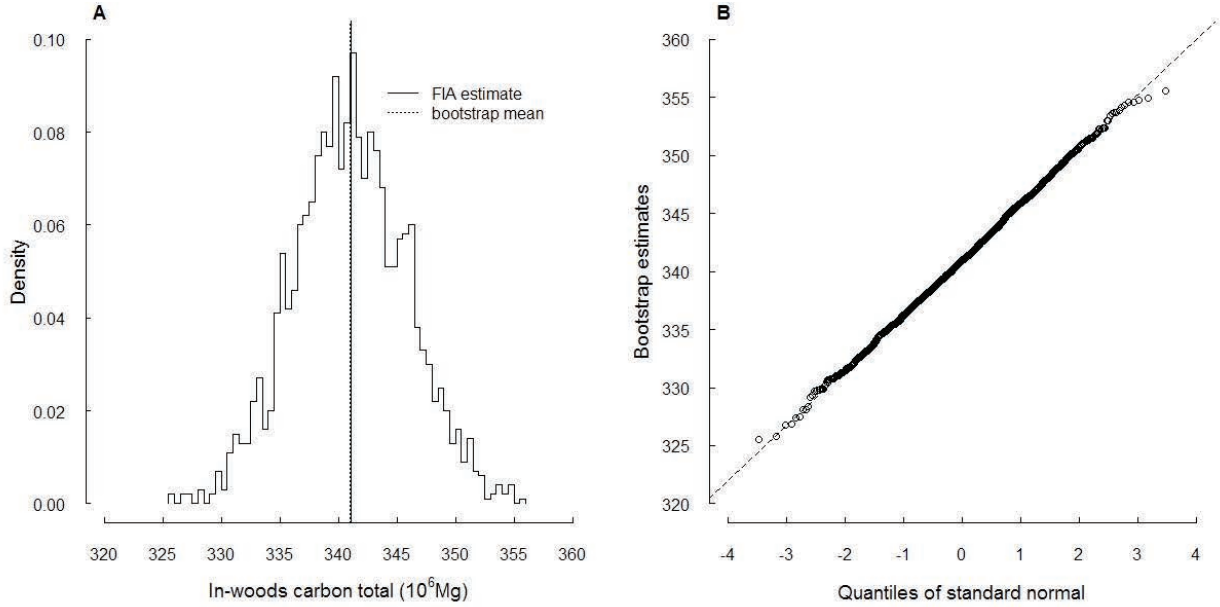

Figure 9—Bootstrap sampling distribution of southwide in-woods carbon totals (10^6 Mg) (A), and its quality of fit based on a normal distribution (B).

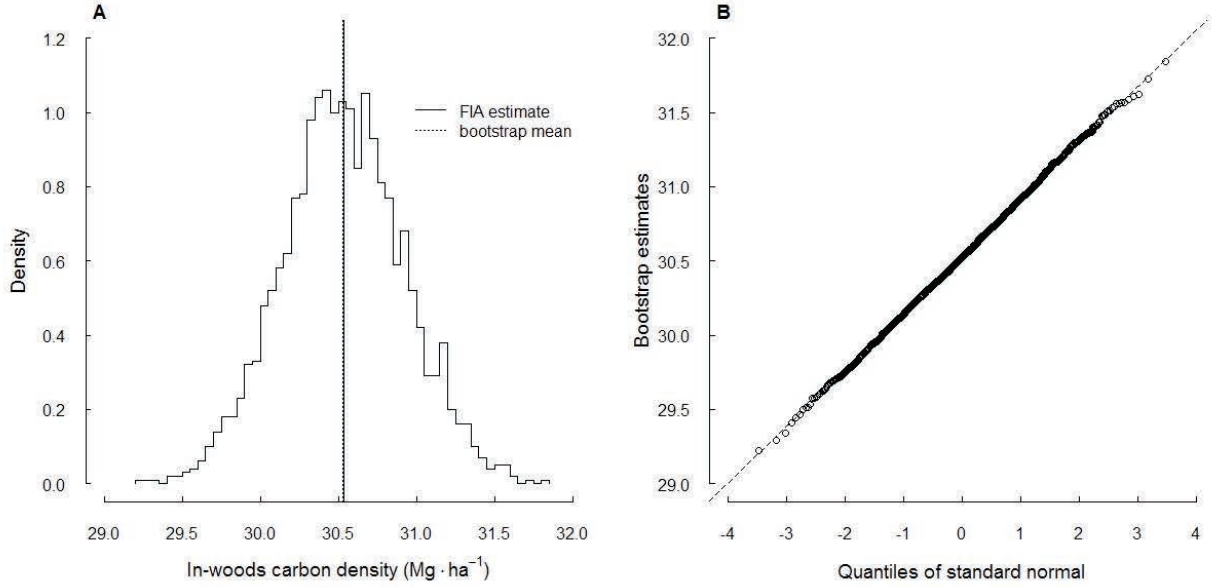

Figure 10. Bootstrap sampling distribution of southwide in-woods carbon mean per hectare (Mg•ha-1) (A), and its quality of fit based on a normal distribution (B).

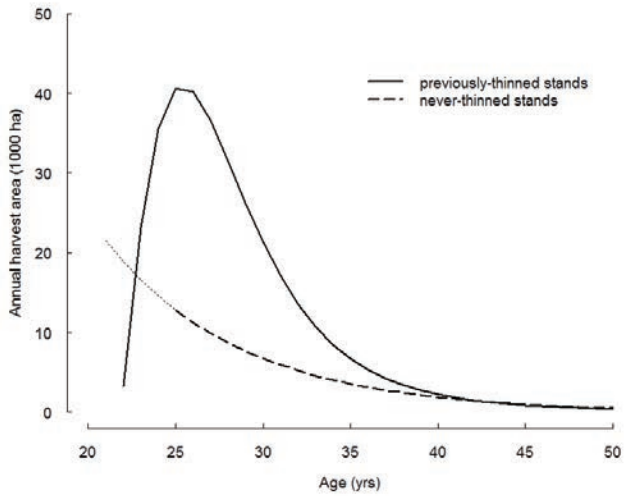

Figure 11—Hypothetical function of annual harvest area on ages, accounting for previous thinning operations. A dotted line represents that annual harvest areas may not be restricted to hypothetical values because areas of predicted rotation ages <25 are less than that of rotation age at 25 years (Figure 5B).

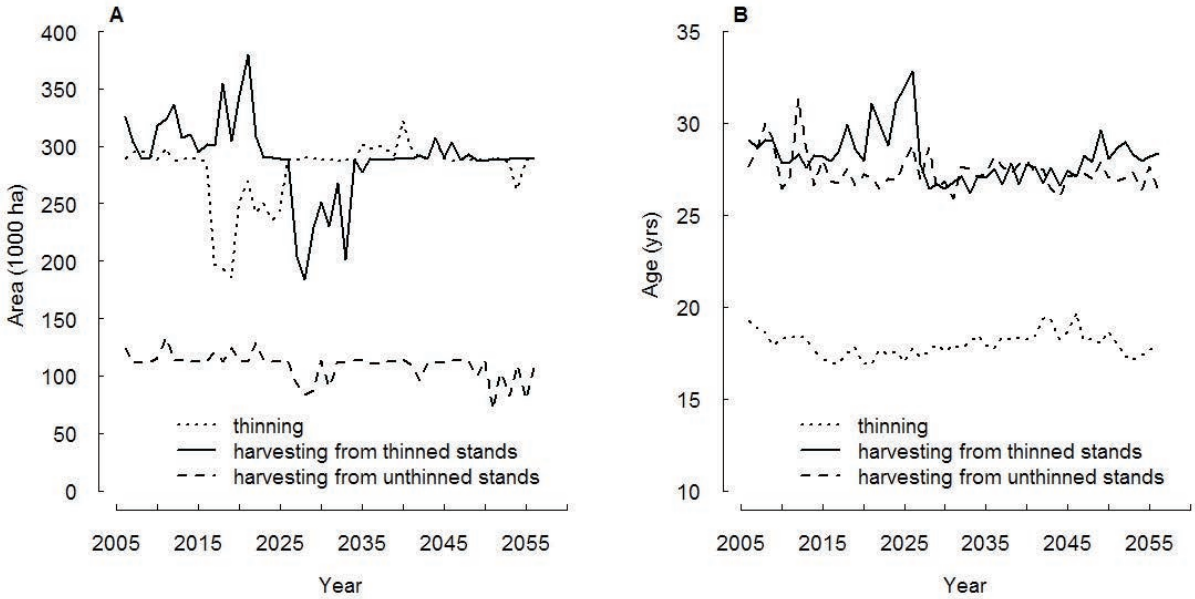

Figure 12—Simulations of area operated each year in the span of 50 years: (A) Area operated by thinning, and final harvest on thinned and unthinned stands; (B) Mean values of ages when activities of timber removed occur.

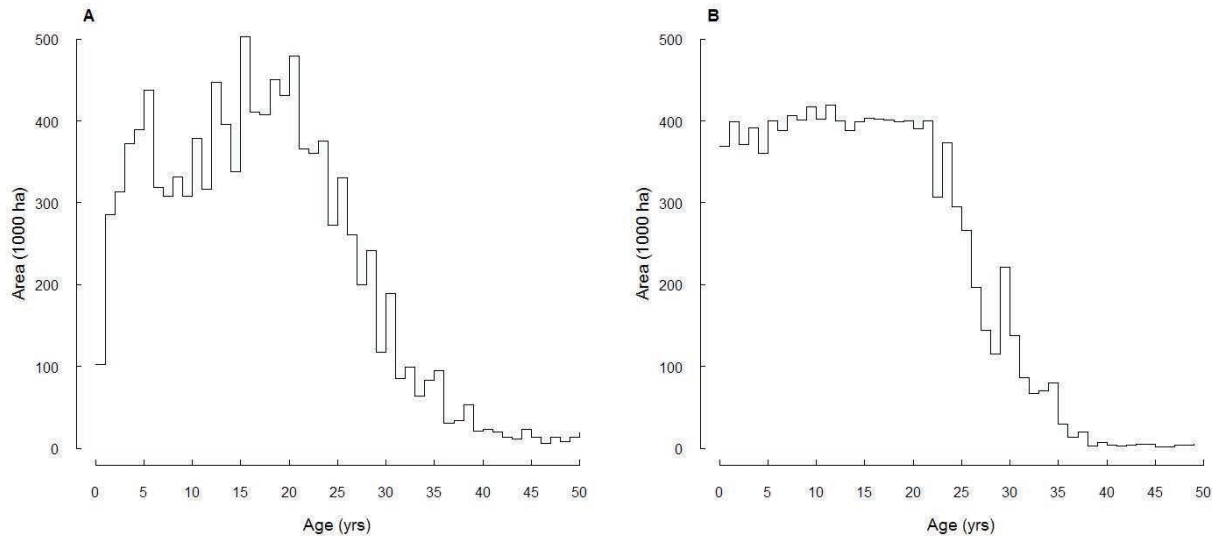

Figure 13—Age-class distribution of loblolly pine plantations throughout the South before and after a 50-year harvest period: (A) Initial plantations based on FIA 2005 – 2007 inventory data; (B) plantations after a 50-year harvest period.

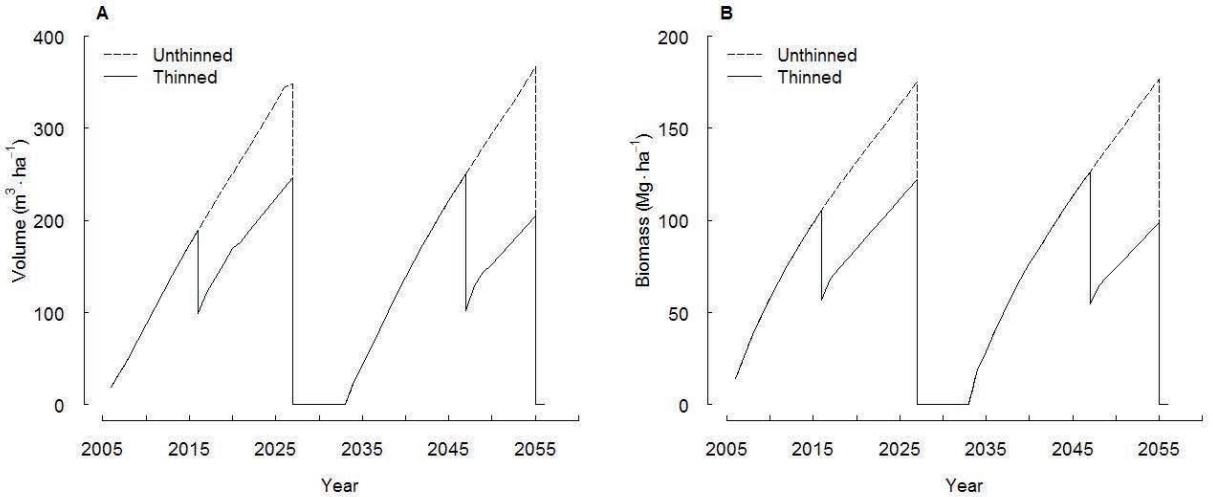

Figure 14—Temporal changes in in-woods stocks of volume (A) and aboveground biomass (B) for two different management regimes: thinned and unthinned planted loblolly pine yield and growth in 50-year projections. Two final harvests occur at age 27 years for each regime. For a thinned stand, thinnings occur at ages 16 and 19.

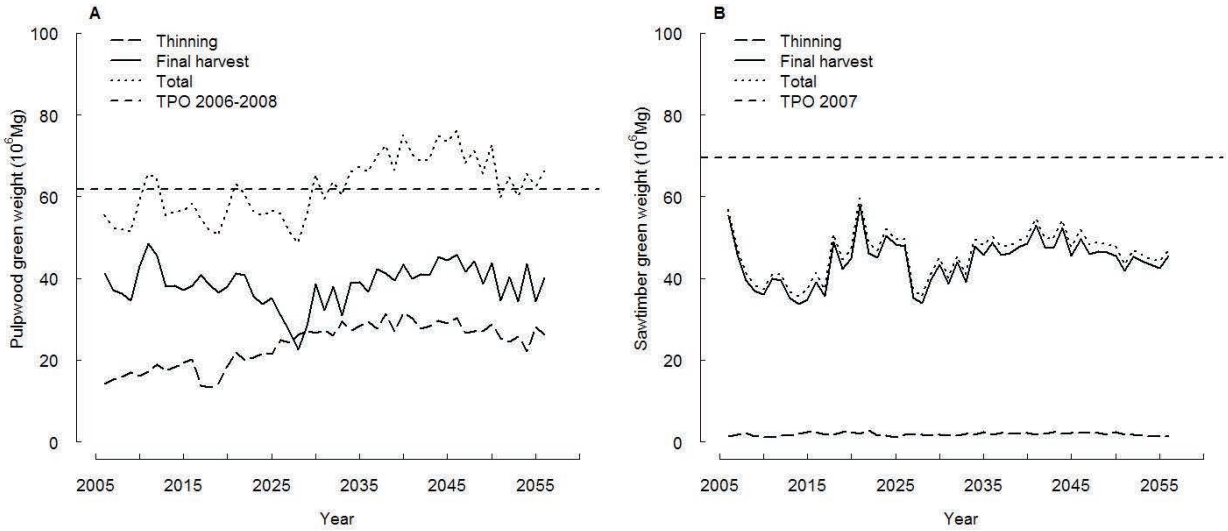

Figure 15—Timber production projections from thinnings and final harvests: (A) Pulpwood; (B) Sawtimber.

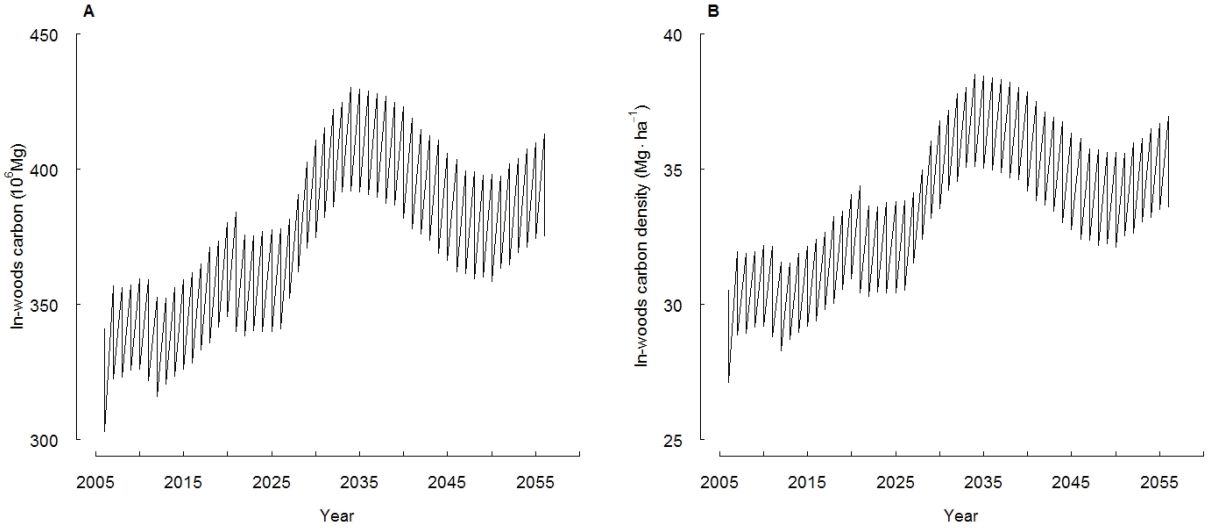

Figure 16—Effects of management activities including planting, thinning, and final harvest on the southern in-woods carbon storage: (A) Carbon total (10^6 Mg); (B) Carbon mean ($Mg \cdot ha^{-1}$).

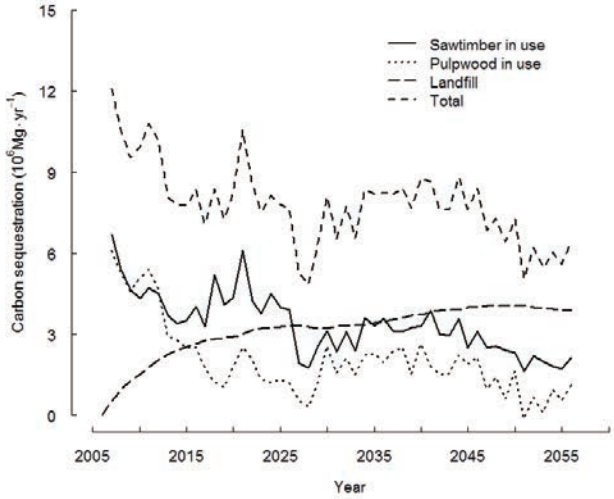

Figure 17—Carbon fluxes in harvested-wood-products pools including products in use and landfills.

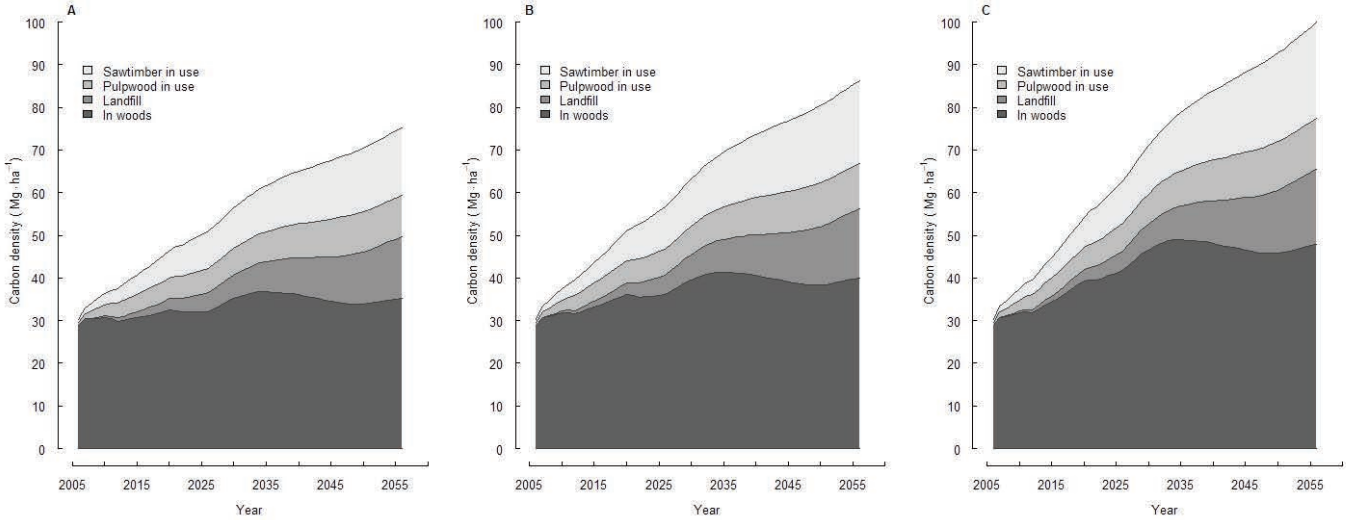

Figure 18—Effects of management intensity on carbon pools of sawtimber in use, pulpwood in use, landfill, and in woods: (A) Baseline management; (B) Management scenario 1 – fertilizer and herbicide application (plus baseline management); (C) Management scenario 2 – planting of genetically improved growing stock and fertilizer and herbicide application (plus baseline management).

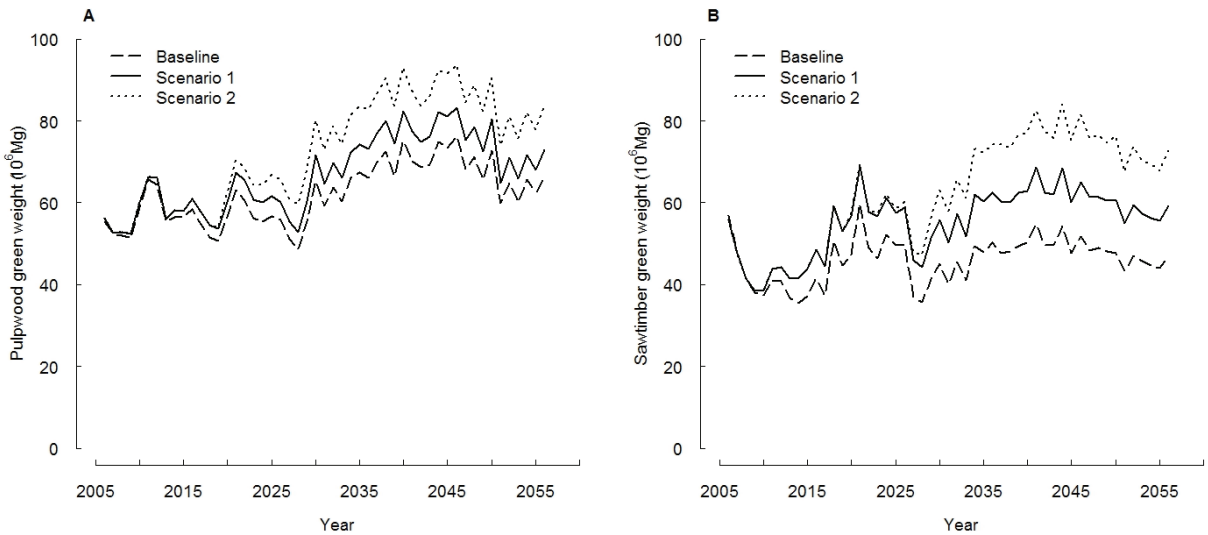

Figure 19—Effects of management intensity on timber production (A) Pulpwood green weight; (B) Sawtimber green weight.

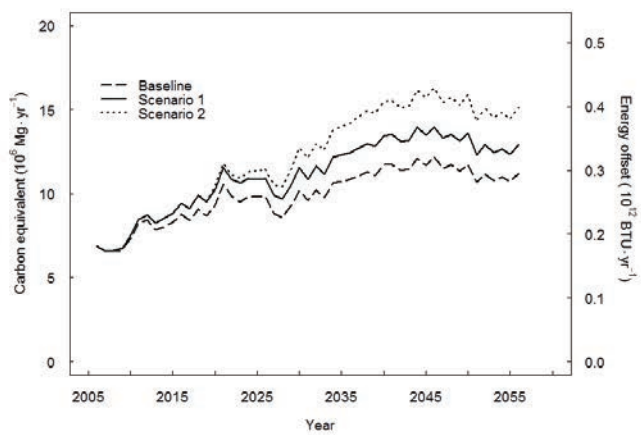

Figure 20—Effects of management intensity on energy offset and assumed energy content of biomass = 38×10^6 BTU/Mg C (U.S. Energy Information Administration, 2010).

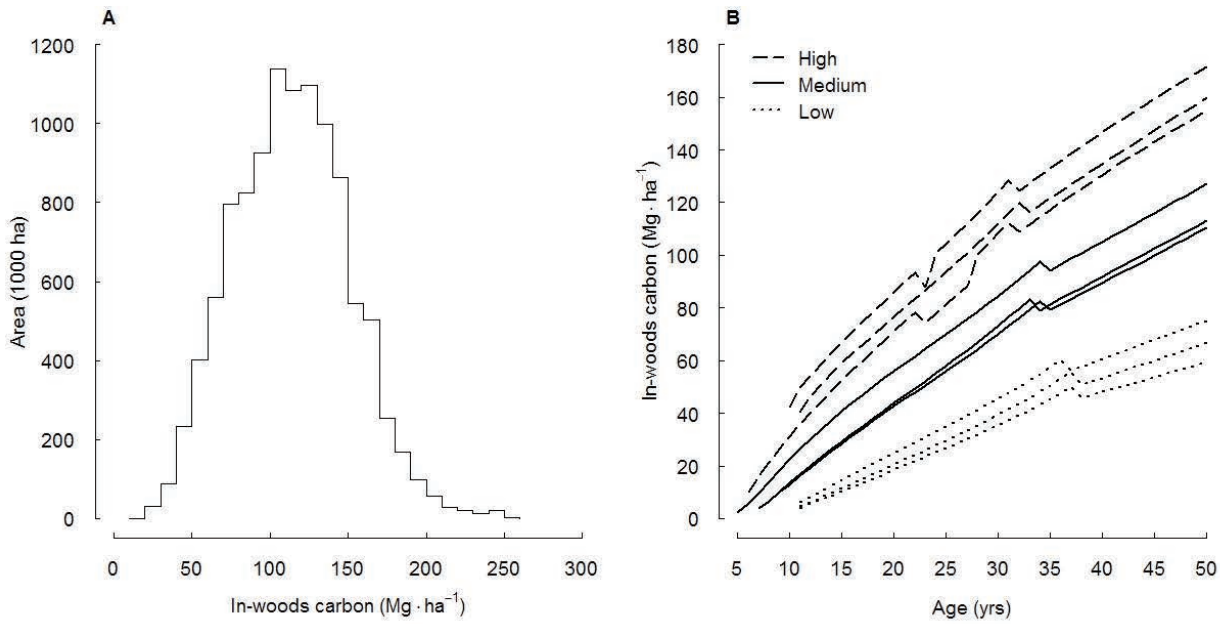

Figure 21—Hypothetical in-woods carbon mass per hectare of loblolly pine plantations across the South after a 50-year unmanaged period: (A) Distribution of carbon mass per hectare; (B) Examples of stand-level carbon mass per hectare (i.e. High, Medium, and Low) which planted stands are no longer being managed at all.